43191

NO. 8

BOREHOLE HYDRAULIC TESTING

FOR AQUIFER CHARACTERIZATION

300252

HAZARDOUS WASTE MANAGEMENT PRACTICE

TECHNICAL MEMORANDUM NO. 8

BOREHOLE HYDRAULIC TESTING FOR AQUIFER CHARACTERIZATION

(JFH/HWMP)

2 September 1987

HAZARDOUS WASTE MANAGEMENT PRACTICE

TECHNICAL MEMORANDUM NO. 8

BOREHOLE HYDRAULIC TESTING FOR AQUIFER CHARACTERIZATION

8.0 INTRODUCTION

The assessment of aquifer characteristics is vital to any investigation of ground water contamination. The existing literature apparently does not provide a comparison of the relative merits of the various techniques for aquifer testing and analyses with respect to hazardous waste site investigations.

This technical memorandum is intended to address portions of that technical gap, and is directed toward the following specific objectives:

- Provide a summary of the various types of testing methods available for application in hazardous waste site investigations.
- Discuss the advantages and disadvantages of the various methods with specific emphasis on the hazardous waste site constraints.
- Identify the most commonly used methods and present field and analytical procedures suitable for WCC operations with examples.
- Provide aids for selecting the appropriate method for specific site conditions.

This discussion is not intended to present a detailed theoretical treatment of ground water movement. Those interested in the theoretical backgrounds for the methods described herein are referred to Walton, 1970; Bouwer, 1978; Freeze and Cherry, 1979; and Todd, 1980.

8.0.1 Major Categories of Aquifer Tests

Estimates of aquifer properties may be obtained utilizing several different categories of testing methods. The primary types considered in this discussion are listed below.

- Areal Aquifer Testing Methods

- Point-Specific Permeability Testing Methods

- Downhole Permeability Testing

The primary goal of any testing method is the development of estimates for the key aquifer parameters listed below.

- Transmissivity (T) is the measure of the overall capability of the formation to produce water, and is usually stated in gallons per day, per foot (English Engineering System) or cubic meters per day, per meter (International System).

- Hydraulic Conductivity (K) is defined as the rate of flow in gallons per day, per square foot (English Engineering System) or cubic meters per day per square meter (International System). It is equal to the transmissivity divided by aquifer thickness ($K = T/m$).

- Permeability (k) is defined as a measure of the capacity of a porous rock for transmitting a fluid and presented in centimeters per second.

- Storativity (S), also known as Storage Coefficient, is the amount of water in storage released from a column of aquifer with unit cross section under unit decline of head for a confined aquifer. It is represented by a dimensionless number.

- Specific Yield (Sy) is the volume of water drained from a unit volume of an unconfined aquifer.

The various categories of testing methods utilize the same basic principles of ground water dynamics. However, each method is directed toward the different aspects of the hydrogeologic setting in which the project is located.

Areal aquifer testing methods are directed toward assessment of the average aquifer parameters of the hydrogeologic system over a relatively large area.

They will normally involve a pumping well that will generate a ground water withdrawal of sufficient quantity to stress the aquifer and one or more monitoring points to measure the ground water surface reactions over the desired vertical and lateral extent of the project area.

Point-specific testing methods are utilized to acquire estimates of permeability at a single point, both vertically and laterally within the project area. The results of these test methods are basically not applicable over the site unless the hydrogeologic system is extremely homogeneous.

Downhole permeability testing is a procedure that allows either point-specific testing methods or areal aquifer testing methods to be applied at vertically discrete intervals within a single borehole or well. Therefore, the procedure is versatile and can be modified to extract more detailed information at specific zones rather than relying on averages derived by the areal aquifer testing methods.

- Develop a base list of references for use in a more complex aquifer characterization, if required by the project work plan.

8.0.2 Advantages and Disadvantages of Test Methods

As with any series of field operations, no system is applicable to every situation. Each of the general categories have advantages and disadvantages, particularly with respect to the strictures imposed in hazardous waste investigations.

8.0.2.1 Areal Aquifer Testing Methods

Advantages

- A large portion of the aquifer is tested and the results are normally more representative of aquifer characteristics.

- Storativity and specific yield values can be estimated.

- Detailed data analyses will allow a more accurate prediction of local and regional anomalies for incorporation into a recovery and remedial plan.

- Dynamics of contaminant migration can often be empirically identified during the test monitoring.

- Vertical and lateral boundaries for the aquifer can be identified and approximately located with a properly designed test.

- Design Parameters for the mechanical components of a contaminant recovery/containment system can be cost-effectively designed.

Disadvantages

- In low permeability aquifers, long-term pumping may be required to complete the test and obtain the reliable estimates.

- Areal pumping effects may modify the ground water flow patterns and temporarily expand the zone of contamination.

- If contamination is present, disposal of discharged water may require special discharge permits and portable treatment plants.

- These tests are more expensive than slug tests due to the need for more extensive drilling and piezometer construction for aquifer analysis.

8.0.2.2 Point-Specific Testing Methods

Advantages

- Estimates can be made in-situ, therefore, errors in laboratory testing of disturbed samples are eliminated.

- Tests are low cost and can be performed quickly due to minimal well drilling and construction requirements.

- Hydraulic conductivity estimates can be obtained for vertically limited, and discrete zones within an aquifer.

- Equipment size and construction requirements allow usage of the methods in a relatively confined space.

- Tests can be performed without addition or removal of water, if appropriate, eliminating the need for disposal of contaminated water or dilution of contaminants around the testing point.

- The method is applicable to lower permeability aquifer material (10^{-2} to 10^{-7} cm/second).

Disadvantages

- Only the hydraulic conductivity of the area immediately surrounding the well is estimated, the average for the area is not estimated.

- Normally, reproducibility of results is only possible within a factor of two.

- Analysis of data requires several assumptions by the geologist/engineer. Inaccuracy in the assumed values will produce erroneous results.

- Storage coefficient(s) cannot be determined.

- Method is not applicable to higher permeability units ($>10^{-2}$ cm/sec).

In summary, the main advantages of this procedure are low cost and flexibility relative to areal location and/or vertical control. Primary disadvantages are the problem of reproducibility and the restricted applicability of the results to the entire aquifer.

8.0.2.3 <u>Downhole Permeability Testing</u>

<u>Advantages</u>

- Zone-specific variability in aquifer parameters can be quantitatively estimated within the same well or borehole.

- Either point-specific or areal aquifer testing methods may be employed, as appropriate, within the different portions of a borehole.

- This testing is useful in locating and assessing the effects of fracturing in bedrock investigations.

<u>Disadvantages</u>

- Results normally apply only to the vicinity of the borehole in the vertical zone isolated.

- Presence of high vertical permeability may allow bypass of the packer systems and produce erroneous results.

- Analytical procedures are highly specific and strongly oriented toward the particular testing array used.

- Injection test procedures require careful monitoring to safeguard against the hydraulic fracturing of bedrock due to overpressure.

- Costs for downhole permeability testing are relatively high due to drilling requirements, on-site equipment arrays during testing and time involved in calibration and collection of data.

The primary advantages of the downhole permeability testing methods are flexibility in using areal or point-specific data acquisition, and the ability to differentiate vertically discrete aquifer properties.

Major disadvantages are the cost of data acquisition and the calibration requirements with some procedures and equipment arrays.

8.0.3 Selected Methods for Estimating Aquifer Parameters

In some projects, field data are not available to allow the preliminary selection of test methods that may be applicable. On such occasions, preliminary characterization of aquifer parameters can be performed by using one or more of the following procedures.

8.0.3.1 Empirical Equations Used to Estimate Specific Capacity and Transmissivity for Higher Permeability Aquifer

Two empirical equations have been developed from the modified non-equilibrium (Jacob) equation to estimate the potential specific capacity and transmissivity of a well. These equations are derived by assuming an average well diameter, average duration of pumping, and typical values for the applicable storage coefficient. The equations are useful for quickly checking the accuracy of values obtained for transmissivity and specific capacity during pumping test.

Jacob's equation can be defined as follows:

$$S = \frac{264Q}{T} \log \frac{0.3Tt}{r^2 s}$$

Where:

s = drawdown in the well, in ft
Q = yield of the well, in gpm
T = transmissivity of the well in gpd/ft
t = time of pumping in days
S = storage coefficient of the aquifer
r = radius of the pumped well, in ft

This equation is based on the simplifying assumptions listed in Section 8.1.3.1. By rearranging the terms, the specific capacity (yield of a well in gpm/foot of pumping drawdown) is identified as follows:

$$\frac{Q}{s} = \frac{T}{264 \log \frac{0.3Tt}{r^2 s}} \qquad (1)$$

If typical values are assumed for the variables in the log function of the equation, such as t = 1 day, r = 0.5 ft, T = 30,000 gpd/ft, and S = 1 x 10^{-3} for a confined aquifer and S = 7.5 x 10^{-2} for an unconfined aquifer, an estimated specific capacity for a confined aquifer is presented by the following equation:

$$\frac{Q}{s} = \frac{T}{2000} \qquad (2)$$

The estimated specific capacity for an unconfined aquifer is provided by the following equation:

$$\frac{Q}{s} = \frac{T}{1500} \qquad (3)$$

These empirical equations can be used to check the transmissivity of wells where the specific capacity is known, or to check the specific capacity where the transmissivity is known.

It may appear presumptuous to use an average transmissivity value, or even assume a transmissivity value, before one is known. However, because transmissivity appears in the log term of Equation 1, the affect on the value of the divisor in either derivation is minimal. For example, if a transmissivity of 120,000 gpd/ft is assumed, the divisor increases from 2,000 to 2,133, a difference of less than 7 percent.

Estimates of Q/s using Equation 3 for the unconfined aquifers will almost always be optimistic because part of the aquifer is dewatered during pumping, and results in a lower transmissivity as the saturated thickness decreases. Therefore, estimates for unconfined aquifers may be more accurate if Equation 2 is used.

These procedures may be applied to a driller's logs with even minimal data on well production and drawdown.

8.0.3.2 Grain-Size-Distribution Curves For Estimating Hydraulic Conductivity

In instances where samples have been obtained from an aquifer, sieve analysis of the samples can be utilized to obtain estimates of hydraulic conductivity for the aquifer.

This method is applicable to units with predominant sand constituents. However, it is not accurate for units with significant clay content.

A comparative set of typical sand distribution curves and estimated values are presented in Figure 8-1.

8.0.4 Criteria for Selection of Testing Method

Although specific site constraints will often dictate the testing methods that can be applied during an investigation, the following discussion is intended to present a methodology for identifying preferred methods for a specific site hydrogeologic framework.

The evaluation process utilizes a matrix prepared by WCC personnel for the U.S. Bureau of Mines. This process involves a weighting procedure cross-indexed with project-specific variables that impact project cost, accuracy of data acquired, and applicability of each method.

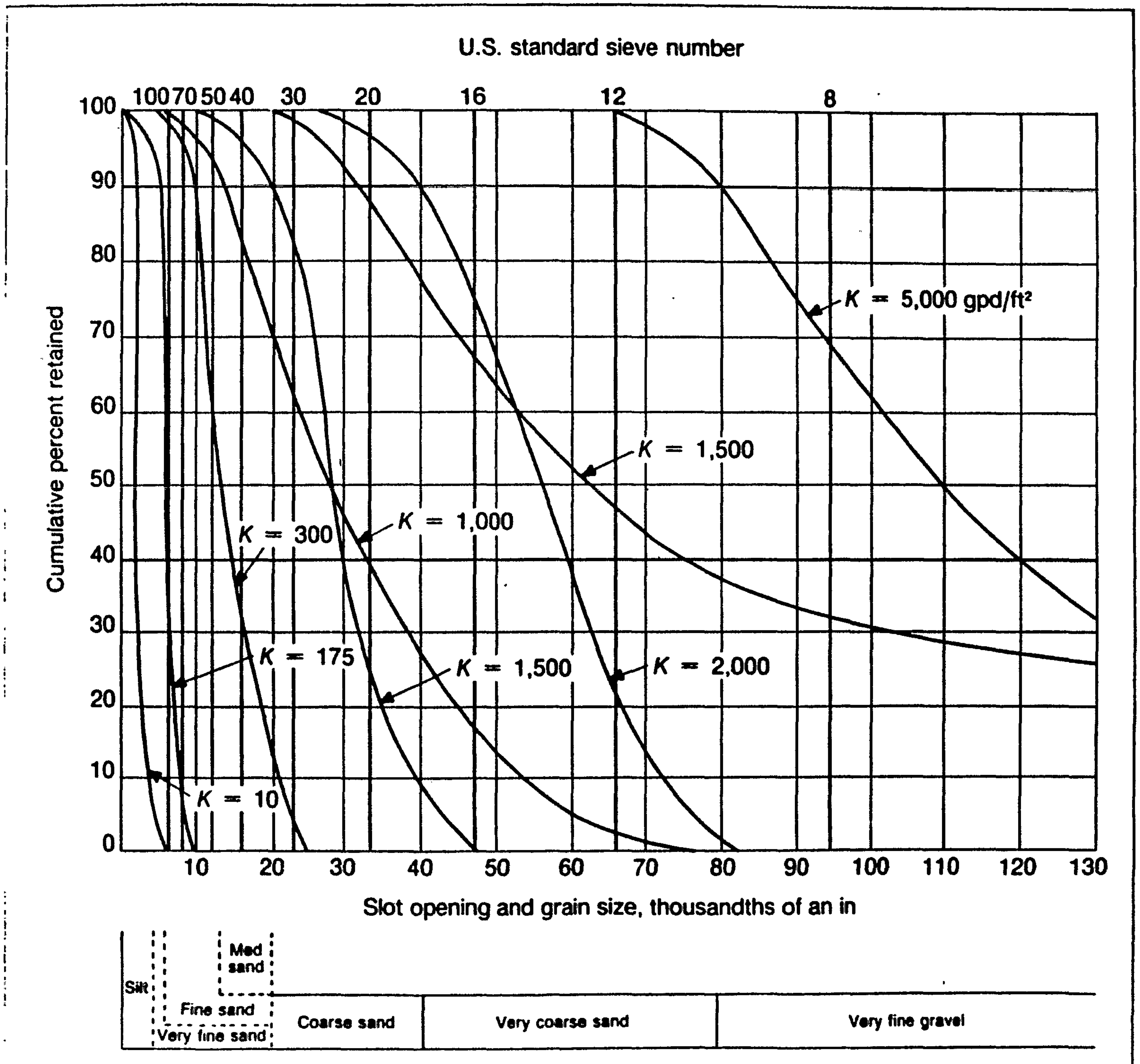
It is not intended to be a final selection method. The procedure should be modified by the field investigator and used as an aid for coordinating project objectives, project constraints, and applicable methodology available.

Permeability Field Test Method Capability Matrix (TMCM)

Test Methods

The TMCM matrix facilitates evaluation of the major acceptable test methods, which are addressed in this memorandum. They are as follows:

- Falling Head Test
- Rising Head Test
- Constant Head Test
- Packer Test with Calibration
- Packer Test with Pore Pressure Transducer
- Well Pump Test, Equilibrium Analysis
- Well Pump Test, Non-Equilibrium Analysis



Fi e (H aul ond ivity be in on the bas of gr -siz istri on c es.

300262

The matrix has been divided into two sections, corresponding to the tests performed above and below the water table (see Figure 8-2). These test methods are evaluated for each criterion based on a relative numerical scale between 1 and 4. The meaning of the values for each criterion is described below.

Evaluation Criteria

Each criterion is used as a basis for the test method evaluation discussed below, including the significance of the rating scale.

Hole Preparation Cost: This criterion pertains to the general cost of preparing the borehole prior to the test. Ratings are based on the preparation of a single borehole except for the well pump tests, where several boreholes are required.

Rating: 4 = least expensive
1 = most expensive

Equipment Cost (Procurement Cost): This criterion reflects the purchase or rental costs for equipment required to perform the test. It is assumed that the relative cost ratings will remain the same whether the equipment is purchased or rented, (i.e., rental rates are proportional to the purchase price). The criterion does not include the cost of hole preparation as this comprises a separate evaluation criterion.

Rating: 4 = least expensive
1 = most expensive

Performance Cost: This criterion reflects the cost of performing the field test, including the required equipment and the staffing consideration.

Rating: 4 = least costly
1 = most costly

Operation Time: This criterion considers the amount of time needed to perform a test. For the packer test, it is assumed that the "continuous test" procedure will be used (see Section 8.3.2). Two ratings are provided for the variable and constant head tests, and reflect the time needed to complete the single test and the stage test procedures.

KEY:

4/1 — upper-left value: Refers to single test; lower-right value: Refers to stage test

NOTE:

4 is most favorable

1 is least favorable

TEST METHOD		HOLE PREPARATION COST	EQUIPMENT COST	PERFORMANCE COST	OPERATION TIME	OPERATION EASE	EASE OF ANALYSIS	ACCURACY WITH DEPTH: SHALLOW (<150 ft)	ACCURACY WITH DEPTH: DEEP (>150 ft)	ACCURACY WITH PERMEABILITY RANGE: HIGH ($k \geq 10^{4}$ cm/sec)	ACCURACY WITH PERMEABILITY RANGE: LOW ($k < 10^{4}$ cm/sec)	GEOLOGIC SENSITIVITY: HOMOGENEOUS	GEOLOGIC SENSITIVITY: STRATIFIED	GEOLOGIC SENSITIVITY: COMPLEX	PERMEABILITY DISCRIMINATION: VERTICAL	PERMEABILITY DISCRIMINATION: LATERAL (AREAL)
ABOVE THE WATER TABLE	FALLING HEAD TEST	3	4	4	4/2	4/2	4	1	1	3	1	2	1/2	1	1/4	1
	CONSTANT HEAD TEST	4	3	4	3/2	4/2	4	2	2	3	2	3	1/2	1	1/4	1
	PACKER TEST WITH CALIBRATION	4	2	2	2	1	4	3	1	4	4	4	4	4	4	1
	PACKER TEST WITH PRESSURE TRANSDUCER	4	2	2	2	1	4	4	4	4	4	4	4	4	4	1
BELOW THE WATER TABLE	FALLING HEAD TEST	3	4	4	4/2	4/2	4	1	1	3	1	2	1/2	1	1/4	1
	RISING HEAD TEST	3	4	4	4/2	4/2	4	1	1	3	1	2	1/2	1	1/4	1
	CONSTANT HEAD TEST	4	3	4	3/2	3/2	4	2	2	3	2	3	1/2	1	1/4	1
	PACKER TEST WITH CALIBRATION	4	2	2	2	1	4	3	1	4	4	4	4	4	4	1
	PACKER TEST WITH PRESSURE TRANSDUCER	4	2	2	2	1	4	4	4	4	4	4	4	4	4	1
	WELL PUMP TEST, EQUILIBRIUM ANALYSIS	1	1	1	1	2	3	4	4	4	2	4	3	3	1	4
	WELL PUMP TEST, NON-EQUILIBRIUM ANALYSIS	1	1	1	1	2	1	3	3	4	3	4	3	3	1	4

Figure 8-2 FIELD TEST METHOD CAPABILITY MATRIX (After WCC, 1977)

Rating: 4 = least time requirements
1 = greatest time requirements

Operation Ease: This criterion reflects the relative ease in conducting a test. It considers the complexity of the equipment and the required competence level of the operator(s). The criterion does not include the analysis or interpretation of the data obtained from the test, as this comprises a separate evaluation criterion.

Rating: 4 = most easy to perform
1 = most difficult to perform

Ease of Analysis: This criterion considers the relative ease of analyzing the test data to calculate a permeability value. The analyses are generally not complicated. Although well pumping test interpretations are the most difficult to perform, an experienced interpreter can obtain additional valuable information about the aquifer from a properly conducted test.

Rating: 4 = relatively easy to analyze
1 = relatively difficult to analyze

Test Accuracy with Depth: This criterion demonstrates the relative accuracy of each test method as a function of the depth of the test section. The rank can be interpreted as the "reliability" of a permeability value obtained with the test method. The category is divided into two classifications: shallow test sections (depths of 150 feet or less) and deep test sections (depths greater than 150 feet). The maximum accuracy of any test method is about 1/2 of an order of magnitude. The significance of a local, "actual" permeability may be limited, since the permeability of many geologic formations can be expected to naturally vary throughout their mass, and such variation may exceed the estimated test accuracy.

Rating: 4 = most accurate
1 = least accurate

Test Accuracy with Permeability Range: This criterion allows evaluation of the relative accuracy of the test method in high and low permeability deposits. For this matrix, high permeabilities are defined as greater than or equal to 10^{-4} cm/sec, low permeabilities as less than 10^{-4} cm/sec.

Geologic Sensitivity: This criterion reflects the ability of the test method to accurately assess the permeability, based on the geologic environment. The category is divided into the following three classifications:

- Homogeneous - the mass is free from unconformities and discontinuities, either lithologic or structural, which is conducive to a consistent permeability value throughout. An example would be a clean, uniform sandstone deposit free of interbeds and clay seams.

- Horizontally Stratified - The mass contains various horizontal discontinuities, mostly lithologic, which result in a vertical variation in permeability. An example would be an alluvial deposit, with frequently occurring interbeds of silt seams, siltstones and shales.

- Complex - The mass contains a complex system of discontinuities, including joints, fractures, fault zones, weathered zones, and lithologic variations. Examples would be fractured or folded sedimentary sequences and tectonic regions with associated joints, faults, and intrusives.

Rating: 4 = most accurate
1 = least accurate

Permeability Discrimination: This criterion provides for an evaluation at the regional extent over which the test method assesses permeability, in either the vertical or lateral (areal) directions.

Several methods contain two rankings for their ability to allow vertical discrimination of variations. The first number refers to a single test, and the second number refers to the multiple stage test procedure. Note that the single test/stage test rankings have corresponding values in the categories "Operation Time", "Operation Ease", and "Geologic Sensitivity: Stratified".

Assumptions are made that well pump tests are conducted with a minimum of three observation wells, and that variable head, constant head, and packer tests are performed in one borehole. The areal representation of data with the latter group of tests is limited. However, it can be improved with a series of tests in a number of boreholes throughout the site.

Rating: 4 = Maximum ability to assess permeability in a vertical/lateral direction

1 = Minimum ability to assess permeability in a vertical/lateral direction

Overall Rating

The overall rating of the different test methods has not been performed. Such an evaluation would be misleading to the investigator, for it would equally weight each of the criteria in the matrix. The intent is for the investigator to enter the matrix, identify which criteria are relevant on an individual priority basis, and select an appropriate method on those criteria.

After determining the most important criteria for his application, the investigator may require a method for combining the individual criterion ratings into one value for overall comparison purposes. The recommended method is to multiply the ratings for any selected matrix criteria by a weighting factor, and then total the adjusted ratings to obtain a composite rating for a particular test method.

8.1 Selected Areal Aquifer Testing Methods

Testing methods applied to an estimation of aquifer characteristics over an extended area require production or injection of water in sufficient quantities to produce a dynamic response in wells that are remote from the pumping site.

The test methods that are most commonly used in areal aquifer characterization are listed below.

- Constant - Rate Discharge Pumping Test
- Variable - Rate Discharge Pumping Test
- Single Well Pumping Tests

8.1.1 Aquifer Test Design

Optimum aquifer characterization from pumping test data requires a pumping well and as many observation wells as possible within the project constraints.

At least two monitoring wells are necessary to allow use of time-drawdown and distance-drawdown analytical techniques. Four wells would be optional for most tests on hazardous waste sites.

8.1.1.1 Location of Observation Wells

The major factors controlling location and observation wells are as follows:

- Is the aquifer confined or unconfined?
- Thickness of the aquifer that will be tested.
- Anisotropy of the aquifer.
- Obvious or known potential aquifer boundaries, whether positive (lake or stream) or negative (low permeability geologic units).
- Site constraints, either physical, regulatory or economic.

The optimum distance at which to locate an observation well from the pumping well is partially controlled by such conditions as whether the aquifer is confined or unconfined. The location of the observation wells generally depends on the following four aquifer conditions:

- In the majority of the aquifers with fully penetrating pumping wells, observation wells should be located at a distance estimated by using the Theis formulation (Theis, 1935). Assumed aquifer parameters are used to select a location that will provide the amount of drawdown required for proper analysis.
- Where thin aquifers with fully penetrating wells occur, confined aquifers should have the closest observation well located at least 25 feet from the pumping well. For unconfined aquifers, observation wells should generally be located 15 to 100 feet from the pumping well.
- In thick, isotropic aquifers with a partially penetrating pumping well, observation wells should be located one and one-half to two times the aquifer thickness from the pumping well.
- For thick, anisotropic aquifers with a partially penetrating well, observation wells should be located at a minimum distance from the pumping well equal to twice the thickness of the aquifer times the square root of the ratio of the horizontal to the vertical hydraulic conductivity.

For the case of a partially penetrating pumping well, the U.S. Department of the Interior (1981) recommends that the Radius (r) to the closest observation well allowable will be calculated by the following equation:

$$r = \frac{1.5\ (aquifer\ thickness)}{(ratio\ of\ radial\ to\ vertical\ permeability)^2}$$

After estimating the optimum distance, observation wells can be intelligently placed to ensure that useful data are collected. Data will be most useful if at least a combination of wells provide time-drawdown data that correspond to both the flat and the curved portions of the Theis type curve. If three wells are installed, one should be placed closer to the pumping well than the estimated ideal location and one should be placed further away.

8.1.1.2 <u>Field Procedures</u>

Aquifer pumping tests require monitoring the water level over time in the pumping as well as the effects in observation well(s) as the pumping well is pumped at a constant rate.

<u>Data Required:</u> The following data must be accurately recorded at the time the test is performed:

- Locations and well names of each observation well and pumping well.
- Distance to all observation wells from pumping wells.
- Elevation and description of each measuring point (specific description of exactly where the measuring references are located at each well); elevations should be recorded to the nearest 0.01 foot. Elevations referenced to a local datum are normally satisfactory.
- Distance from the land surface to each measuring point to the nearest 0.1 foot.
- Dates of the test and exact times of all measurements (times can be rounded to the nearest minute after 10 minutes have elapsed).

- The relevant well construction data including well depth, well diameter, well casing type, annular seal type, method and location, pump setting, screened interval locations, screen diameter, screen type, and outside diameter of filter pack.

- Pumping well discharge rate.

- Depth to the water below measuring point in all wells including pumping well; data should be recorded to the nearest 0.01 foot.

The wells should be pretested to ensure that they are responding properly (i.e., in good hydraulic communication with the aquifer). Well development may be needed for wells that need rehabilitation. If insufficient data are known about the aquifer's parameters, the development of the pumping well may be a good opportunity to obtain qualitative data to plan the aquifer pumping test. A variable-rate, step-drawdown test (see Section 8.1.4) may be included in the well development work to evaluate a practical pumping rate for the test.

Plans for handling the pumping well discharge also need to be prepared in advance of the test. Discharge must be routed to a location that will not interfere with the pumping well or observation well drawdown data due to the potential for recirculation of the discharge by surface infiltration. An unconfined aquifer is especially susceptible to discharge routing problems as is a limestone aquifer with extensive solution or "piping" characteristics.

Gauges, transducers, and flow meters used in conducting pumping tests should be calibrated before use at the site. Copies of the documentation for instrumentation calibration should be obtained by the hydrogeologist and later filed with the test data recorded. Calibration records will consist of laboratory measurements with any on-site zero adjustment and/or calibration.

In cases where a weir or an orifice is used to measure flow rates, the device should be checked on-site using a container of measured volume and stopwatch. Accuracy of the meters must be verified before proceeding with the testing.

Whenever practical, it is advisable to monitor the pretest water levels at the test site for approximately one week prior to performing the test. This can be accomplished by using a continuous-recording device such as a Stevens Recorder or a pressure transducer with a computerized data-loading system.

This information allows for an evaluation of the barometric efficiency of the aquifer when barometric records are available. It also helps to determine if the aquifer is experiencing an increase or decrease in head with time due to recharge or pumping in the nearby area.

Changes in the barometric pressure are recorded during the test (preferably with an on-site barograph) to correct water levels for possible fluctuations that may occur due to the changing atmospheric conditions. Pretest water level trends are projected for the duration of the test. These trends and/or barometric changes are used to "correct" water levels during the test. Therefore, the water levels will be representative of the hydraulic response of the aquifer due to pumping of the test well.

It is important to consider the potential outside influences on water levels in the test area. Interferences such as tides and nearby pumping wells can render data useless, unless they can be explained. In addition to the pretest monitoring, it is advisable to consider monitoring ground water trends after the test has been completed to compare with pretest trends. A control well outside of the influence of the test but reasonably close can also be monitored to correct for unexpected rainfall or other influences on the hydrogeologic system.

8.1.2 <u>Aquifer Test Procedures</u>

During an aquifer test, water levels should be measured to provide at least ten observations of drawdown within each log cycle of time. The U.S. Department of the Interior (1981) recommends the following schedule for water level measurements.

- For 0 to 10 minutes: 1, 1.5, 2, 2.5, 3.25, 4, 5, 6.5, 8, and 10 minutes;
- For 10 to 100 minutes: 10, 15, 20, 25, 30, 40, 50, 65, 80, and 100 minutes; and
- From 100 minutes to completion: 1- to 2-hour intervals.

During the early portion of the test, sufficient personnel should be available. At least one person should be located at each observation well and at the pumping well, unless remote controlled pressure transducers and computerized data acquisition units are available.

After the first two hours, two people are usually sufficient to continue the test. It is not necessary that the readings at the wells be taken simultaneously. However, it is very important that the depth to water readings be accurately measured and that the exact time be recorded for each measurement. A typical aquifer pump test data form is shown in Figure 8-3.

Test duration is often determined by project constraints with respect to economics, regulatory restrictions (water discharge permits), on-site client activities, and aquifer capabilities. General rules for planning the test pumping duration are as follows:

- For confined aquifers, a minimum of 24 hours pumping time and 3 hours recovery monitoring should be the target. If an evaluation of the geologic framework suggests the presence of hydrogeologic boundaries (lateral facies changes, leaky aquitards, and valley wall boundaries) the test should be extended until the effects of the boundaries can be assessed, if possible.

- For unconfined aquifers, the potential complications of delayed gravity drainage and slow response are due to the migration dynamics and require longer pumping durations to obtain measurable reactions in the observation wells. For planning purposes, a target minimum of 72 hours pumping time and 6 hours of recovery monitoring should be incorporated into the budget. If the geologic setting also indicates the potential for positive or negative boundaries, the test should be extended, if possible, to assess the potential impact.

These test durations should be considered as <u>ideal</u> minimums. When site and project constraints do not allow extended pumping, the data acquisition program should be designed for flexibility to apply analytical techniques that permit multiple cross-checking of aquifer parameters and behavior.

8.1.3 Constant-Rate Discharge Pumping Test - Definition and Analytical Methods

A constant-rate discharge pumping test refers to a procedure where an aquifer is subjected to continuous stress by either production or injection of water at a constant rate for an uninterrupted, specified interval of time.

The amount of reaction within the aquifer is measured in the pumping well and other selected observation wells located in the designated test area as recommended in Section 8.1.2.

Once the data have been acquired, they may then be analyzed by one or more techniques based upon the Theis Equation and the modifications developed by various workers to fit different sets of field conditions.

Although a number of these analytical techniques are available for use, the majority of the situations can be analyzed by utilizing one or more of the following methods. Theoretical treatments of the development of these formulas can be obtained from the general texts listed in Section 8.0.

A simplified data set has been included to illustrate the basic techniques of analysis (See Table 8-1).

The data have been used to construct time-drawdown plots for both the Theis Type curve and the Jacob-Cooper analyses.

8.1.3.1 **<u>The Theis Non-Equilibrium Equation - (Type Curve)</u>**

The Theis non-equilibrium equation was developed to consider the effect of length of pumping on well yield. By using this formula, the transmissivity (T) and the storativity (S) of the aquifer can be estimated from the data obtained during the early stages of pumping instead of waiting until water levels in the observation wells have virtually stabilized or reached equilibrium conditions. The aquifer coefficients can also be derived from the time-drawdown or recovery measurements in a single observation well (including the pumping well).

Derivation of the Theis equation is based on the following assumptions:

1. The water-bearing formation is uniform in character and the hydraulic conductivity is the same in every direction.

2. The formation is uniform in thickness and infinite in areal extent.

3. The formation does not receive recharge from any source.

4. The pumped well penetrates, and receives water from, the full thickness of the water-bearing formation.

5. The water removed from the storage is instantaneously discharged when the head is lowered.

6. The pumping well is 100-percent efficient.

7. Water removed from the well originates from the aquifer storage.

8. Laminar flow exists throughout the well and the aquifer.

9. The water table or potentiometric surface does not have a slope.

The applicability of these assumptions to actual conditions, and the constraints imposed on data interpretation by these assumptions are discussed in Section 8.1.5.

TABLE 8-1

Drawdown Measurements in an Observation Well
400 Ft (122 m) from Pumped Well
(After Driscoll, 1986)

Time Since Pump Started, in Min.	Drawdown, s ft	Drawdown, s m	Time Since Pump Started, in Min.	Drawdown, s ft	Drawdown, s m
1	0.16	0.05	24	1.58	0.48
1.5	0.27	0.08	30	1.70	0.52
2	0.38	0.12	40	1.88	0.57
2.5	0.46	0.14	50	2.00	0.61
3	0.53	0.16	60	2.11	0.64
4	0.67	0.20	80	2.24	0.68
5	0.77	0.23	100	2.38	0.73
6	0.87	0.27	120	2.49	0.76
8	0.99	0.30	150	2.62	0.80
10	1.12	0.34	180	2.72	0.83
12	1.21	0.37	210	2.81	0.86
14	1.30	0.40	240	2.88	0.88
18	1.43	0.44			

Analytical Procedure for Basic Type-Curve Analysis:

1. Plot field data on log-log graph paper.
2. Select match point as appropriate.
3. Identify values for u and $W_{(u)}$ and insert into formulas for calculation of T and S.

   For this data set, at match point 1/u = 100;
   $W_{(u)} = 4.038$;

$$T = \frac{114.6W_{(u)}}{s} = \frac{114.6(500gpm)(4.038)}{2.3} = 101{,}000gpd/ft$$

$$S = \frac{uTt}{1.87r^2} = \frac{1(101{,}000)0.058}{100(1.87)(400)^2} = 1.9X10^{-4}$$

The theory and assumptions presented basically apply to all equations used in evaluating aquifer characteristics. A simplified treatment of the theory is listed below and provides a background to understand the equations that are discussed in subsequent sections.

The Theis Equation, in its simplest form, is as follows:

$$s = \frac{Q}{4\pi T} W(u)[1440\,\mathrm{min}/days] = \frac{114.6}{T} QW(u)$$

Where:

s = drawdown in feet at radial distance r from the pumping well

Q = pumping rate in gpm

T = coefficient of transmissivity of the aquifer, in gpd/ft of water-bearing formation.

W(u) = the well function of u and is short for the exponential integral written below.

$$W(u) = {}_u\int^{\infty} \frac{e^{-u}}{u} du = -0.5772 - \log_e u + u - \frac{u^2}{2 \cdot 2} + \frac{u^3 \ldots}{3 \cdot 3}$$

In the above expression, $u = 7.48\ r^2\ s/4T = 1.87r^2S/Tt$

Where:

r = distance from the pumping well, in ft
S = storativity, dimensionless (ft^3/ft^3)
T = coefficient of transmissivity, in gpd/ft
t = time since pumping started in days

The use of the Theis Equation to estimate T and S from a pumping test requires water level measurements in the pumping well and, if possible, at least one observation well.

Storativity can be calculated after estimating transmissivity by use of the formula:

$$S = \frac{uTt}{1.87r^2}$$

Examples of the plotting procedure, type-curve matching with data and calculations for transmissivity and storativity using the above formulas are presented in Figures 8-4 through 8-9 for non-leaky artesian and leaky artesian conditions. Both time-drawdown and distance-drawdown techniques are shown.

TABLE 8-2

Well 19 Near Dieterich, Illinois
(From Walton, 1962a.)[a]

Time After Pumping Started, min.	Drawdown, ft.
5	0.76
28	3.30
41	3.59
60	4.08
75	4.39
244	5.47
493	5.96
669	6.11
958	6.27
1,129	6.40
1,185	6.42

[a] Q = 25 gpm and r = 96 ft

Calculation Procedure for Time-Drawdown Data Analysis - Leaky Artesian System.

1. Plot field data and match the data plot with the appropriate component of the family of type curves in Figure 8-6.

2. By interpolation, select an appropriate match point and identify designated values of u, $W_{(u,\ r/B)}$, s and t.

3. Calculate the desired parameters as follows:

$$T = \frac{114.6QW_{(u,r/b)}}{s} = \frac{114.6(2.5)1.0}{1.9} = 1510 \quad gpd/ft$$

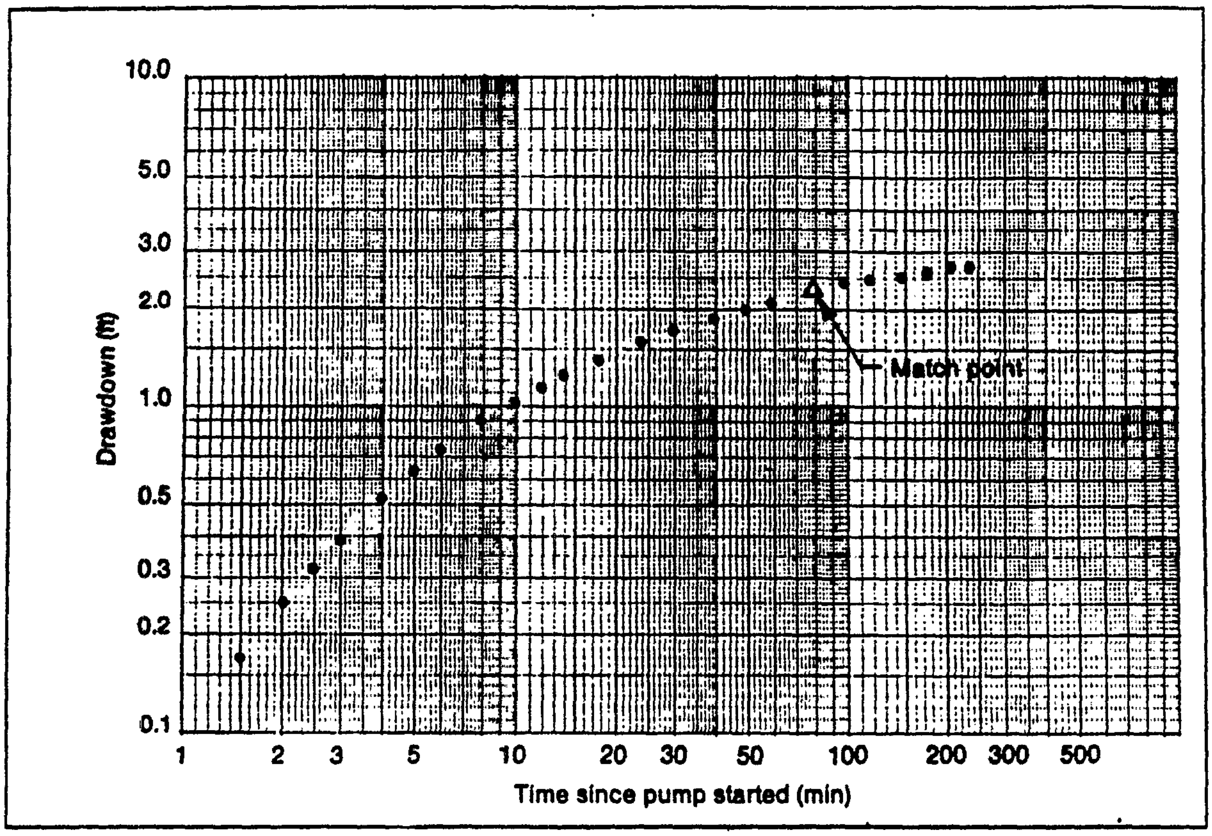


Figure 8-4 **Data given in Table** 8-1**plotted on logarithmic graph paper, define a curve similar in shape to the type curve** (After Driscoll, 1986)

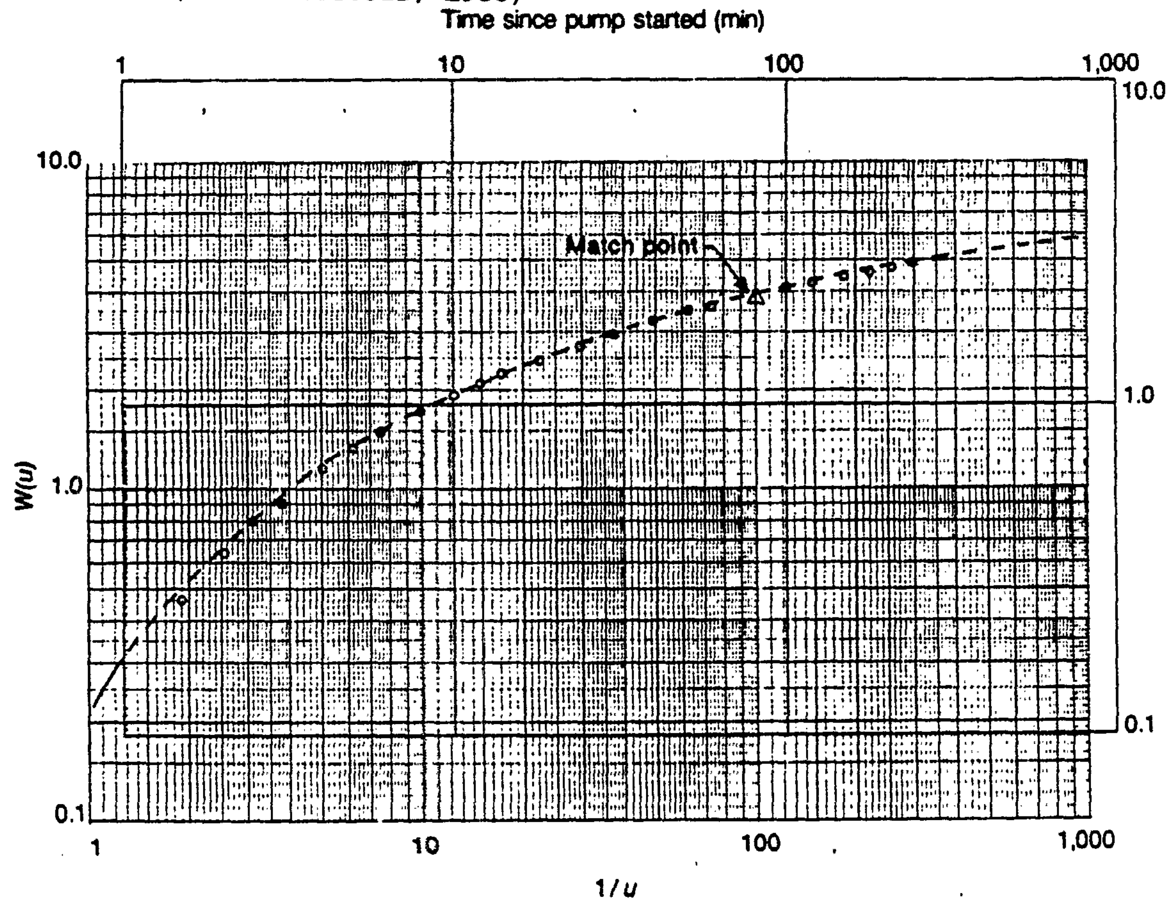


Figure 8-5 **Diagı ɩm of plotted points representing pumping test data superimposed on the type curve. Match point chosen for $1/u$ = 100.** (After Driscoll, 1986)

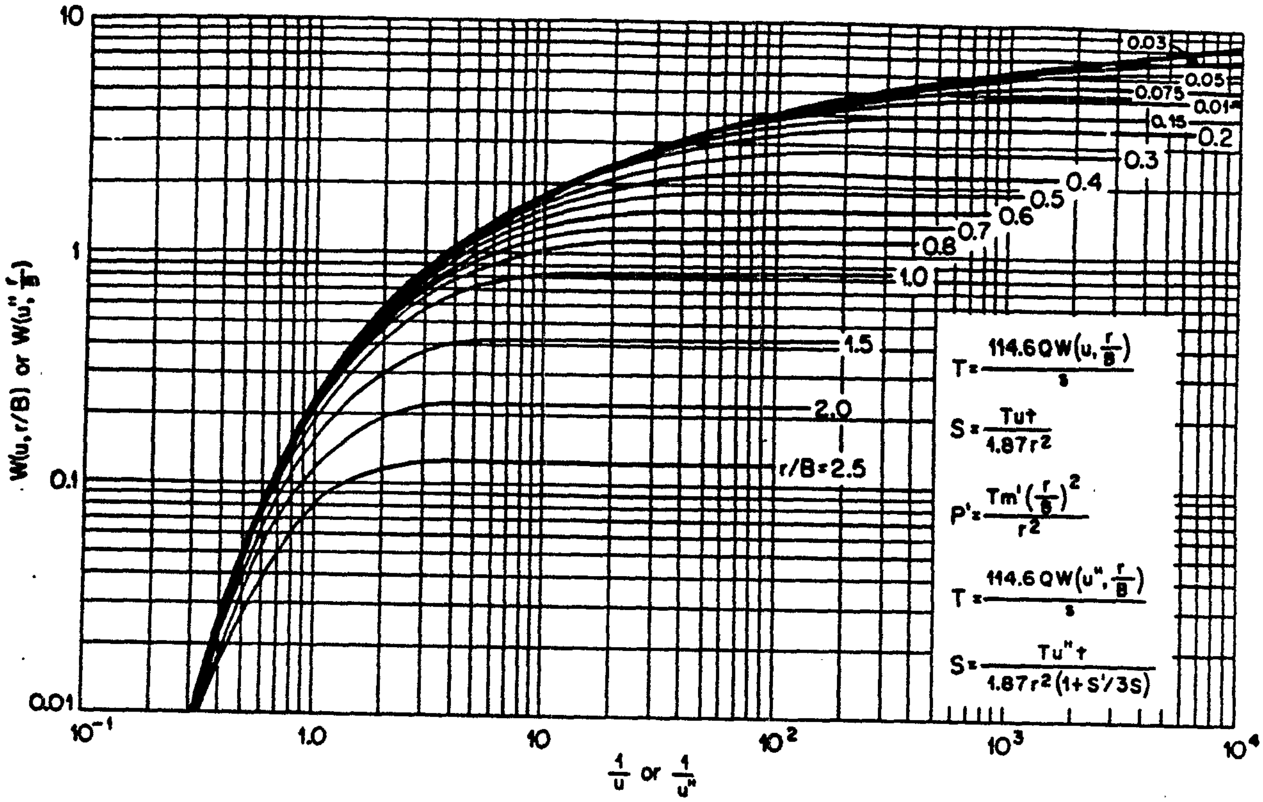


Fig. 8-6 Leaky artesian, fully penetrating, without water released from storage in aquitard, constant-discharge, time-drawdown type curves. (*After Walton, 1962a.*)

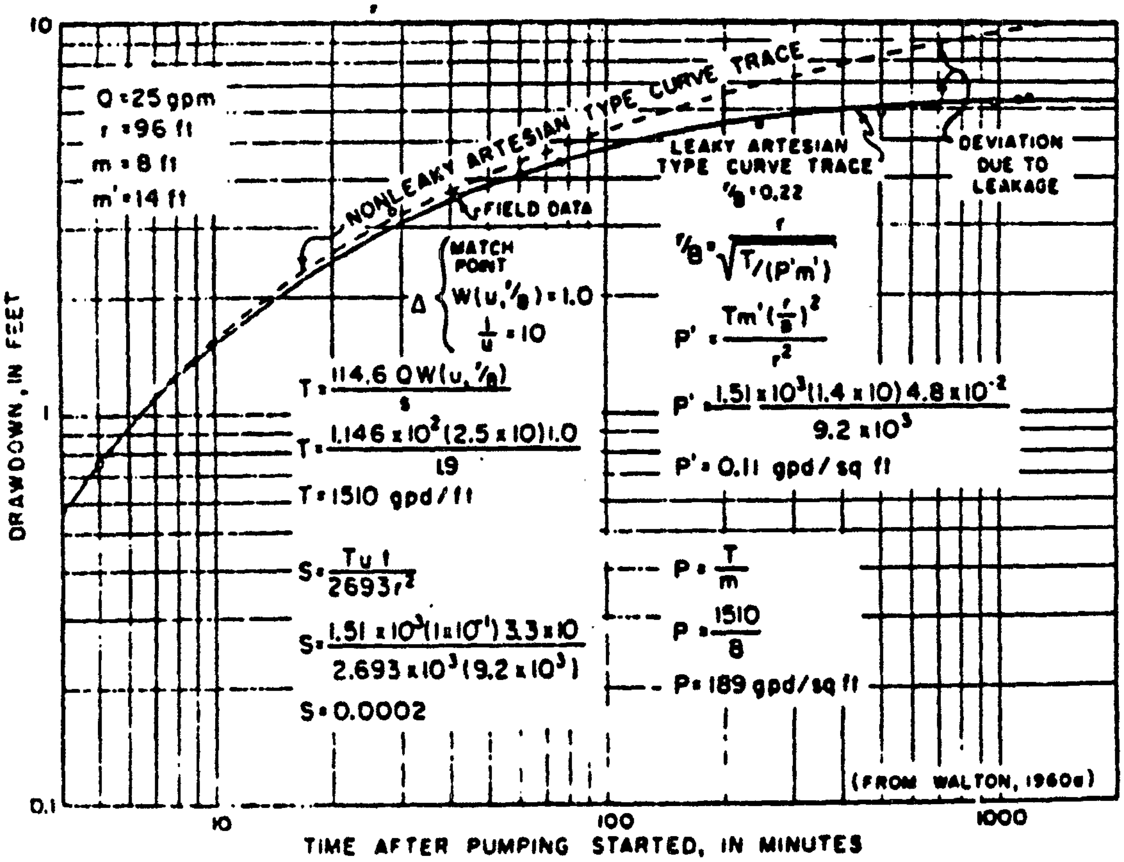


Figure* 8-7 *Time-drawdown graph for well 19 near Dieterich
(After Walton, 1962)

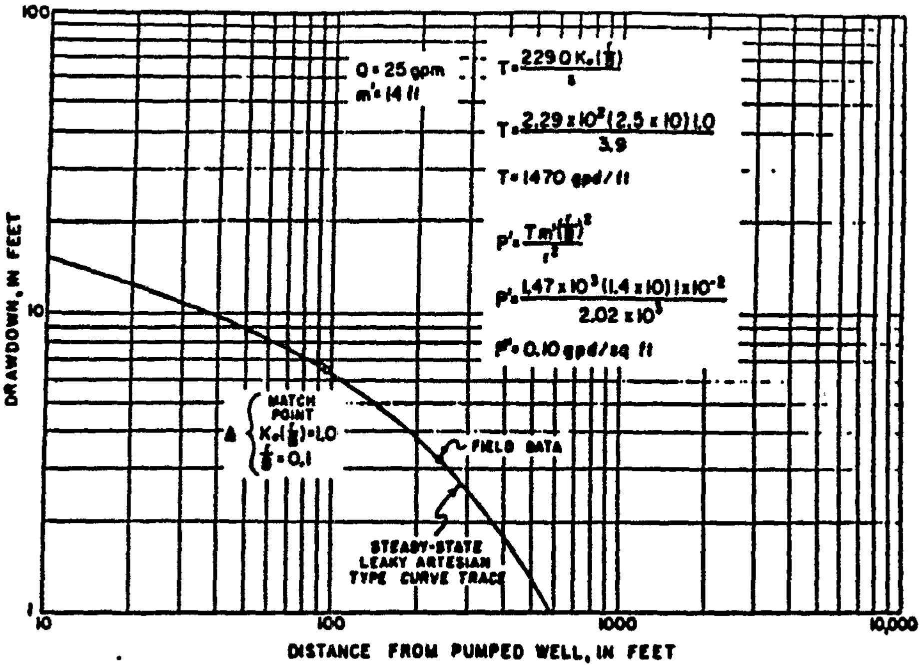


Fig. 8-8 Distance-drawdown graph for test near Dieterich, Illinois. (*From Walton, 1960.*)

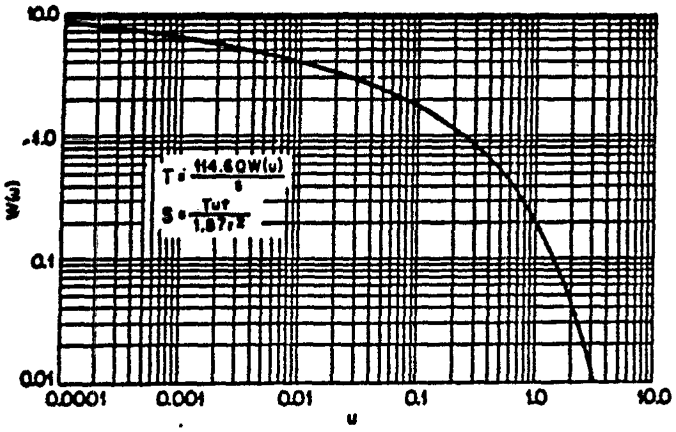


Fig. 8-9 Nonleaky artesian, fully penetrating, constant-discharge, distance-drawdown type curve. (*Drawn by W. C. Walton.*)

TABLE 8-3 DISTANCE-DRAWDOWN DATA FOR TEST NEAR DIETERICH, ILLINOIS. (*From Walton, 1962a.*)[a]

Well no.	*Distance from pumped well, ft*	*Drawdown, ft*
15	234	3.25
16	92	6.70
19	94	6.42

[a] Q = 25 gpm and t = 1,185 min.

Similar calculations can be developed using distance-drawdown data from the same test (see Table 8-3) to illustrate time-drawdown, leaky effects calculations (see Figures 8-8 and 8-9).

Calculation procedures in this method involve the following:

1. Graph field data on log-log graph paper.
2. Identify the best fit match for the data using the appropriate type curve.
3. Extracting the values for K_o (r/B), r/B, s and r, Calculate T and P' as follows:

$$T = \frac{229\ Q\ K_o\ (r/B)}{s} = \frac{229\ (25)\ 1.0}{3.9} = 1470 \text{ gpd/ft}$$

$$P' = Tm'\ (r/B)^2 = 1470\ (14)\ (.1) = 0.10 \text{ gpd/sq ft}$$

Where:

P' = Average permeability of the aquitard

m' = Thickness of the aquitard

300280

$$S = \frac{Tut}{2693r^2} = \frac{1510(.1)33}{2693(9200)} = .0002$$

$$P' = \frac{Tm'(r/B)^2}{r^2} = \frac{1510(14).048}{9200} = 0.11 \quad gpd/sq.ft.$$

Where P' is the average permeability of the leaky aquitard overlying the aquifer being tested.

8.1.3.2 <u>Cooper-Jacob Modification of Theis Equation (Semi-Log Method)</u>

One of the commonly used analytical procedures is based upon the fact that when u is less than 0.05, the non-equilibrium formula can be modified to a straight line equation.

This procedure allows the data acquired during the pumping test to be plotted on semi-log graph paper and analyzed with several alternate methods based upon the following simplified transformation.

When analyzing the Modified Theis Equation, Jacob plotted on semi-log paper the various values of W(u) vs. log u. Jacob noted that when u is sufficiently small (0.05 or less), the non-equilibrium formula can be modified to a straight line equation:

$$w(u) = 2.3 \quad \log u - 0.5772$$

For small values of u, the curve very nearly parallels the asymptote with slope = -2.3. Therefore, the Type Curve Equation written in the two-point form is:

$$Y_2 - Y_1 = m(x_2 - x_1)$$

And becomes:

$$W(u)_2 = 4s\pi T/Q \quad \text{and} \quad u = 7.48r^2 s/4Tt$$

Thus:

$$s_2(4\pi T/Q) - s_1(4\pi T/Q) = -2.3 \quad \log \quad u_2/u_1$$

300281

And:

$$(s_2 - s_1)(4\pi T/Q) = +2.3 \ \log \frac{7.48 r_1{}^2 \ \ S/4Tt_1}{7.48 r_2{}^2 \ \ S/T4t_2}$$

Which finally reduces to:

$$(s_2 - s_1) = \frac{2.3Q}{4\pi T} \ \log \frac{r_1{}^2/t_1}{r_2{}^2/t_2}$$

For constant values of r (i.e., one observation well) the equation becomes:

$$(s_2 - s_1) = \frac{2.3Q}{4\pi T} \ \log \frac{t_2}{t_1}$$

And for one log-cycle of time (t = 10 to 100 min.), the equation becomes:

$$s = \frac{2.3Q}{4\pi T} \ x \ (1440 \ \mathrm{Min}/Day)$$

Or:

$$T = \frac{264Q}{\Delta s}$$

Where:

T = coefficient of transmissivity, in gpd/ft
Q = pumping rate, in gpm
Δs = drawdown per log-cycle of time in one well, in feet.

Calculations of the Coefficient of Transmissivity and Storage can be performed by utilizing the following equations:

$$T = \frac{264Q}{\Delta s}$$

Where:

T = transmissivity
Q = pumping rate
Δs = drawdown differential per log-cycle of time

And:

$$S = \frac{0.3\ Tt_o}{r^2}$$

Where:

S = storativity
T = Transmissivity
T_o = straight line plot to 0 (zero) drawdown (in days)
r = distance to observation well (in feet)

These formulas are applicable to observation well data. However, only transmissivity can be calculated from the pumped well. The plotting and the calculation procedures used in this technique are illustrated in Figure 8-10, again using data from Table 8-1.

Water level recovery data collected from the testing array can also be used to calculate T and S values for each well. These values provide an excellent cross-check for estimates of aquifer parameters.

However, in this instance, the dynamic changes measured are calculated recovery (s-s') on arithmetic scales is illustrated in Figure 8-11. For analysis, the data must be plotted on a semi-log graph paper and treated with the following modified formulas:

For Calculated recovery:

$$T = \frac{264Q}{(s-s')};\quad S = \frac{0.3Tt'_o}{r^2}$$

Where the terms are the same as previously defined except:

t'o = the projection of a straight line based upon recovery data to 0 drawdown.

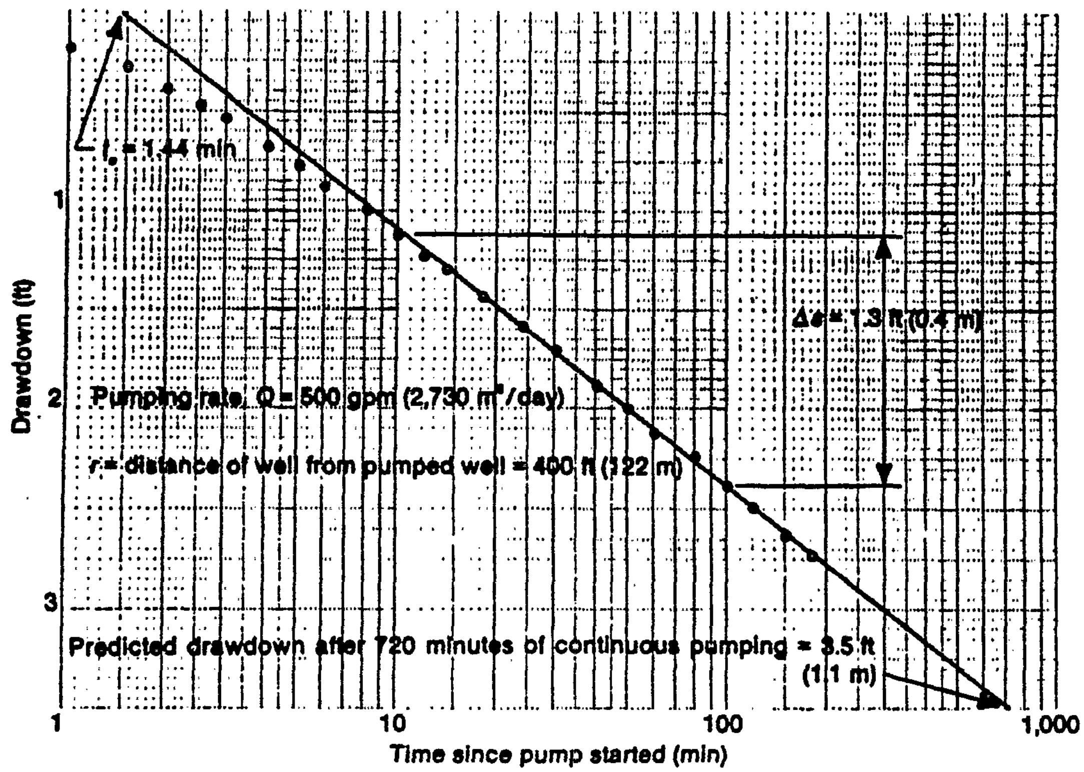


Figure 8-10 Semi-Log Plot of Data from Table 8-1

To calculate appropriate aquifer parameters:

1. Graph data.

2. Estimate Δs from best fit line through data plot.

3. Calculate T and S using the following equations:

$$T = \frac{264\ Q}{\Delta s} = \frac{264\ (500\ \text{gpm})}{1.3} = 101{,}538\ \text{gpd/ft}$$

$$S = \frac{0.3\ Tt_0}{r^2} = \frac{0.3\ (101{,}538)\ \frac{1.44}{1440}}{400^2} = \frac{0.3\ (101{,}538)\ .001}{160{,}000} = .00019$$

Table 8-4 **Residual Drawdown and Calculated Recovery in the Observation Well** (Driscoll, 1986)

Time since pump started, t	Time since pump stopped, t'	Ratio, t/t'	Depth to water*		Residual drawdown*, s'		Drawdown, s, from pumping curve†		Calculated recovery $(s - s')$	
min	min		ft	m	ft	m	ft	m	ft	m
500	0	—	18.60	5.67	10.60	3.23	10.60	3.23	0.00	0.00
501	1	501.00	18.55	5.66	10.55	3.22	10.60	3.23	0.05	0.01
502	2	251.00	18.50	5.64	10.50	3.20	10.60	3.23	0.10	0.03
503	3	168.00	18.40	5.61	10.40	3.17	10.61	3.23	0.21	0.06
504	4	126.00	18.09	5.52	10.09	3.08	10.61	3.23	0.52	0.15
506	6	84.00	17.72	5.40	9.72	2.96	10.62	3.24	0.90	0.28
508	8	64.00	17.22	5.25	9.22	2.81	10.63	3.24	1.41	0.43
510	10	51.00	16.64	5.07	8.64	2.63	10.64	3.24	2.00	0.61
520	20	26.00	15.27	4.66	7.27	2.22	10.67	3.25	3.40	1.03
530	30	17.70	14.50	4.42	6.50	1.98	10.70	3.26	4.20	1.28
540	40	13.50	13.63	4.16	5.63	1.72	10.73	3.27	5.10	1.55
560	60	9.35	12.95	3.95	4.95	1.51	10.80	3.29	5.85	1.78
590	90	6.55	12.01	3.66	4.01	1.22	10.96	3.34	6.95	2.12
650	150	4.33	10.80	3.29	2.80	0.85	11.15	3.40	8.35	2.55
710	210	3.38	10.70	3.26	2.70	0.82	11.35	3.46	8.65	2.64
770	270	2.85	10.06	3.07	2.06	0.63	11.56	3.52	9.50	2.89
830	330	2.51	9.96	3.04	1.96	0.60	11.76	3.59	9.80	2.99
890	390	2.28	9.60	2.93	1.60	0.49	11.95	3.64	10.35	3.15

*Static water level, 8 ft (2.44 m)
†Average pumping rate during preceding pumping period was 200 gpm (1,090 m^3/day)

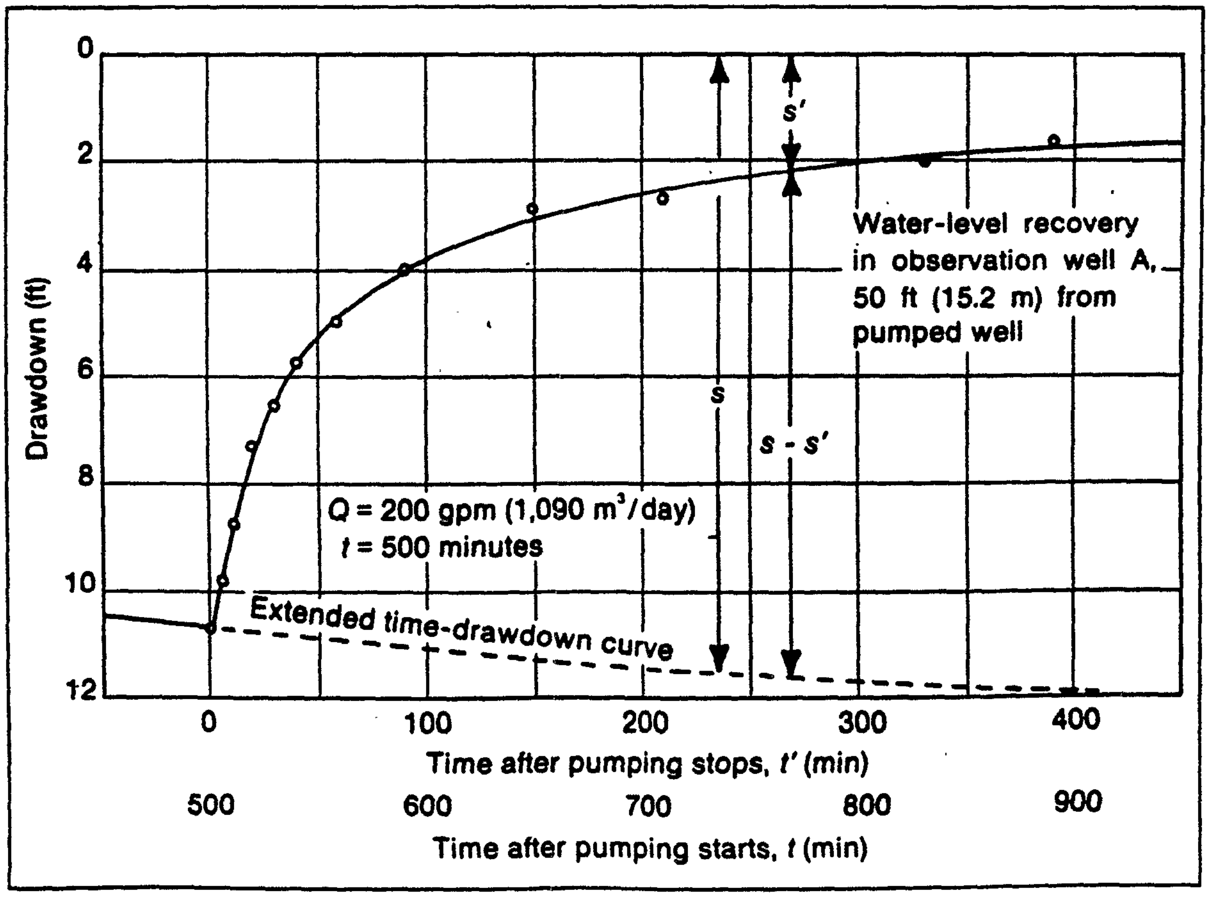


Figure 8-11 Residual-drawdown curve from observation well, with extended time-drawdown curve (on arithmetic scales) showing how calculated recovery is determined at any instant during the recovery period. Producing well pumped 200 gpm (1,090 m^3/day) for 500 minutes. (Driscoll, 1986)

For residual drawdown:

$$T = \frac{264Q}{\Delta s}$$

In this instance, the residual drawdown (s) should be plotted against t/t'.

Where:

t = time since pumping began
t' = time since pumping ceased

Although transmissivity can be calculated by utilizing t/t' plots, storativity can only be estimated from calculated recovery and derived from observation wells not the pumping well.

The plotting procedure and the calculations for using time-recovery and residual drawdown techniques are illustrated in Figures 8-12 and 8-13, using data from Table 8-4.

When at least two monitoring wells are available, the areal effects generated by the pumping test can be plotted on semi-log paper and utilized to estimate T and S for the aquifer. The basis for this procedure is described, in summary, below.

When the basic equation is changed to reflect a constant time t, and drawdown of two separate observation wells, the equation becomes:

$$s_2 - s_1 = \frac{2.3Q}{4\pi T} \log \frac{r_1}{r_2}$$

And for one log-cycle of radial distance, r from the pumping well (i.e. $r_1 = 10$, $r_2 = 100$ and $s_1 < s_2$). Also, if r_2 is greater than r_1, then s_1 will be greater than s_2 and the equation becomes:

$$s_1 - s_2 = \frac{2(2.3Q)}{4\pi T} \log \frac{r_2}{r_1} \text{ (1440 min/day)}$$

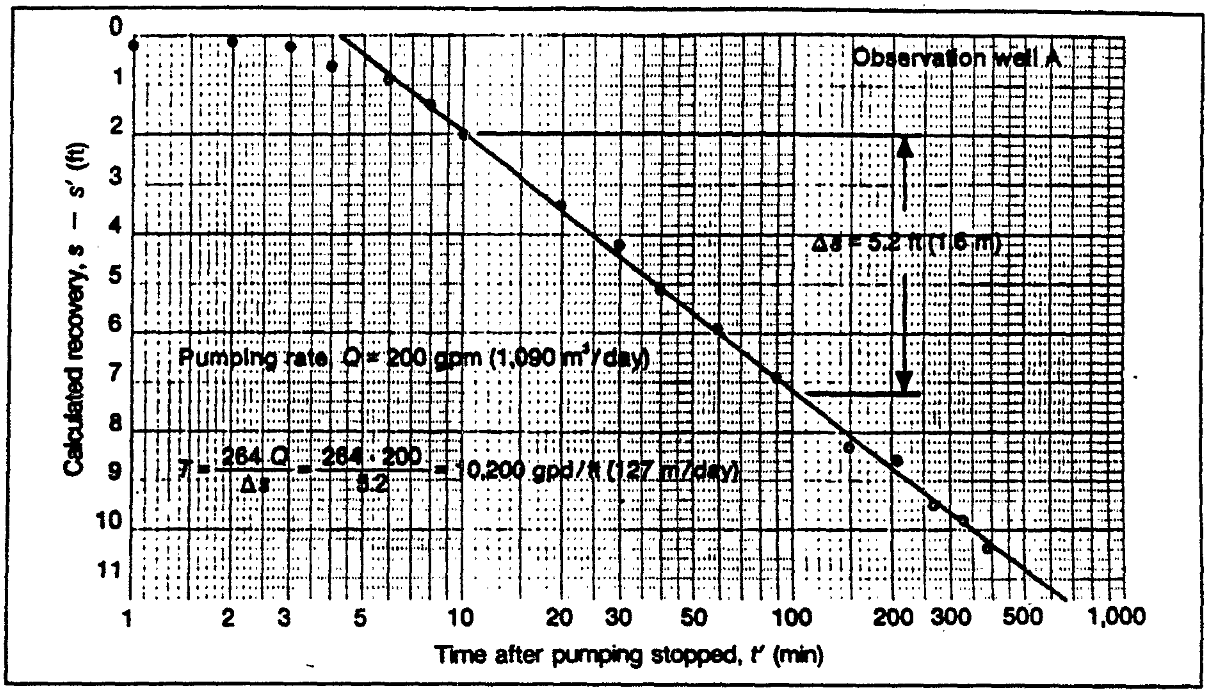


Figure 8-12 **Time-recovery plot for observation well becomes a straight line when plotted on a semilog diagram, similar to the time-drawdown diagram for the preceding pumping period.** (After Driscoll, 1986)

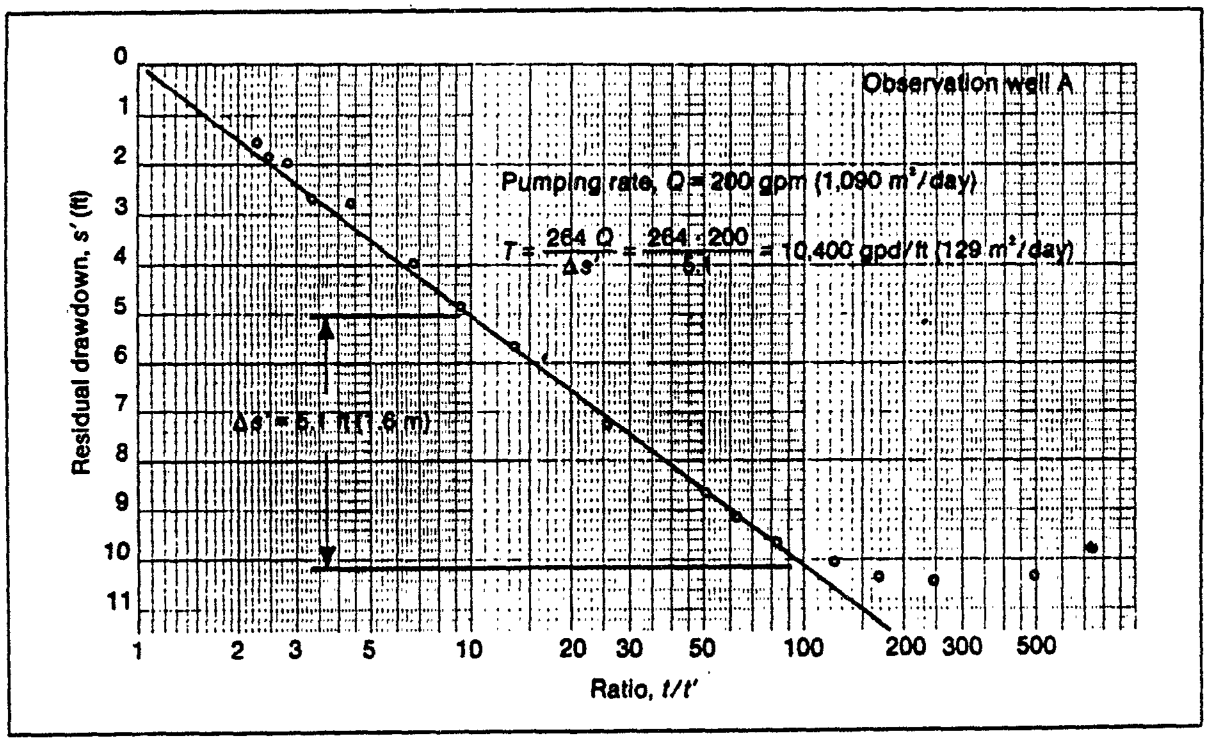


Figure 8-13 **Residual drawdown plotted against the ratio *t/t′* becomes a straight line on semilog graph and permits calculation of transmissivity as shown. Time during recovery period increases toward the left in this diagram.** (After Driscoll, 1986)

And for one log-cycle of r, the equation reduces to:

$$T = \frac{528Q}{\Delta s}$$

Where:

T = transmissivity, in gpd/ft
Q = pumping rate, in gpm
Δs = drawdown per log-cycle of radial distance, in feet.

When the basic Modified Theis Equation is used, the storativity equation can be derived.

$$W(u) = -2.3 \log u - 0.5772$$

$$s(4\pi T/Q) = 2.3 \log \frac{\pi 4Tt}{7.48r^2 s} - 2.3 \log 1.78$$

Where:

0.5772 = 2.3 Log 1.78

Simplifying and combining:

$$s = \frac{2.3Q}{4\pi T} \log \frac{t}{r^2} - \frac{2.3Q}{4\pi T} \log \frac{S}{.301T}$$

When s = 0 in s vs. log t plot, the above equation becomes:

$$S = 0.3T\frac{(t_o)}{r^2}$$

Where:

S = storage coefficient, ft^3/ft^3
T = coefficient of transmissivity, in gpd/ft
t_o = intercept of the straight line at s = 0, in days
r = distance from the pumped well to observation well where observations were made

The plotting procedure and the methods of calculation for this technique are presented in Figure 8-14.

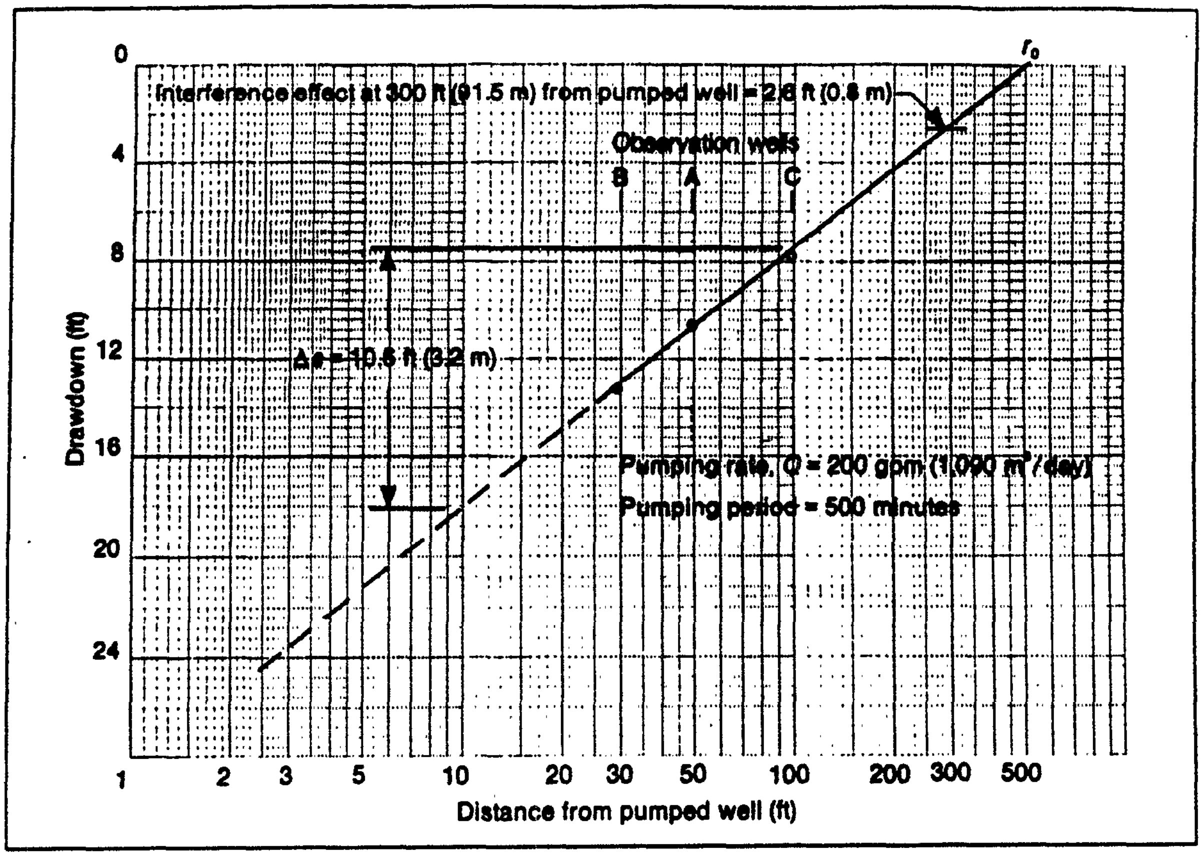


Figure 8–14 Trace of the cone of depression plotted on semilogarithmic graph paper becomes a straight line. Drawdown in each observation well was measured 500 minutes after start of the pumping test.
(After Driscoll, 1986)

To Calculate Aquifer Parameters;

1. Graph data.
2. Estimate Δs from best fit line through data plot.
3. Calculate T and S using the following procedure:

$$T = \frac{528\ Q}{\Delta s} = \frac{528\ (200)}{10.6} = 9{,}962 \text{ gpd/ft}$$

$$S = \frac{0.3\ Tt_o}{r_o^2} = \frac{0.3\ (9{,}962)\ \frac{500}{1440}}{(500)^2} = .0041$$

Wherever possible, multiple analytical methods should be applied to the data. This will allow the establishment of good cross-checks on data reliability. It will also allow identification of potential anomalies related to test perturbations or to aspects of the geologic framework, which were not evident prior to the test.

The analytical results should <u>always</u> be evaluated with respect to the geologic setting in which the test has been performed. Hydrogeologic models derived from these data should include identified boundaries from geologic investigations, as well as those that are noted during the test.

8.1.4 Variable Head Test - Definition and Analytical Procedures

The most common type of variable discharge test is the step-drawdown test. In this test, the well is pumped at several successively higher pumping rates and the drawdown for each rate, or step, is recorded. Pumping times should be the same for each step and usually range from 1/2 to 2 hours, dependent upon aquifer type and reaction time.

If time permits, the water level should be allowed to recover to static level between each step. The test should includes a minimum of three steps and normally include from five to eight.

The step-drawdown test can be used for the following purposes:

- This procedure will aid in estimating the specific capacity of the well at various discharge rates. Selection of preferred pump design and production rates can then be made accurately.
- Partition of total head loss into portions attributable to laminar flow (formation loss) and turbulent flow (well inefficiency) can be performed.
- Estimates of Transmissivity and Storage Coefficient can be obtained by data plots for one of the constant-rate steps of the test.

Analytical Procedures for Step-Drawdown Data

Procedures for analysis of data from a step-drawdown data are based upon a combination of methods proposed by Jacob (1947) and Bierschenk (1964).

For laminar flow conditions in a 100% efficient well, drawdown in a confined aquifer can be expressed as follows:

$$s = \frac{264Q}{T} \log \frac{(0.3Tt)}{r^2 S}$$

Substituting:

$$B = \frac{264}{T} \log \frac{(0.3Tt)}{r^2 S}$$

The equation can be shortened to:

$$s = BQ$$

For a specific well, the value of B is time-dependent. However, since it has minimal change after a reasonable pumping duration, it can normally be assumed to be a constant.

Drawdown in the well can be expressed as the sum of a laminar (first-order) component and a turbulent (second-order) component.

$$s = BQ + CQ^2$$

Using this equation, Bierschenk (1964) presented a simple graphical method for estimating B and C. Dividing the equation by Q and rearranging terms yields:

$$\frac{s}{Q} = CQ + B$$

Note that this is a linear equation in s/Q and Q. That is, if s/Q is plotted against Q, the resultant graph is a straight line with slope C and intercept B (see Figure 8-15, Table 8-5). Thus, B and C can be calculated from this graph.

Inverting the terms shows how specific capacity declines as discharge increases (only with turbulent flow present):

$$\frac{Q}{s} = \frac{1}{CQ + B}$$

Observing the change in drawdown and specific capacity with increased discharge provides information required to select optimum pumping rates.

A parameter often computed from a step-drawdown test is the ratio of the laminar head loss to the total head loss, expressed as a percentage:

$$L_p = \frac{BQ}{BQ + CQ^2} x 100$$

Thus L_p is the percentage of the total head loss that is attributable to laminar flow.

TABLE 8-5

Discharge and Drawdown Data from Typical Step-Down Test
(After Driscoll, 1986)

Yield		Drawdown		
gpm	m^3/day	ft	m	s/Q
514	2,801	13.0	4.0	0.0253
1,066	5,810	27.0	8.2	0.0253
1,636	8,916	43.4	13.2	0.0265
1,885	10,273	61.5	18.8	0.0326
2,480	13,516	82.5	25.2	0.0333
3,066	16,710	101.5	30.9	0.0331
3,520	19,184	120.5	36.7	0.0342

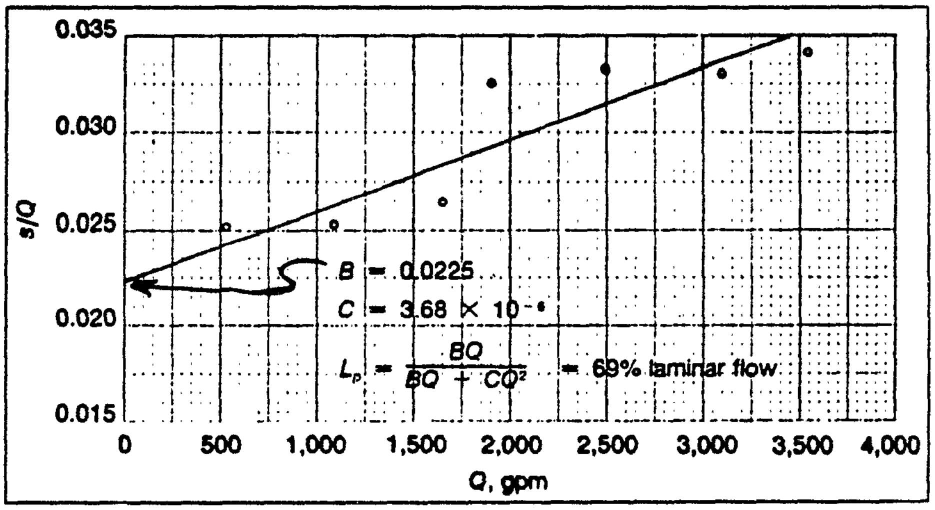


Figure 8-15 Values for *B* and *C* in the step-drawdown equation can be determined from a graph where *s/Q* plotted against *Q*, *(After Driscoll, 1986)*

Procedure for Analysis of Step-Down Data.

1. Plot data from test on arithmetic graph paper.

2. Identify slope of best-fit line (c) and y intercept of plotted line (B)

3. Calculate $$L_p = \frac{BQ}{BQ-CQ^2}$$

For above data set:

$$B = 0.225;\ C = 3.68X10^{-6};\ Q = 2700\ \ gpm$$

$$L_p = \frac{0.0225\ (2700)}{0.0225\ (2700)\ +\ 3.68x10^{-6}\ (2700)^2}(100) = 69\%$$

Thus 69% of the total loss is attributable to laminar flow.

If the assumptions made by Jacob were correct, that is, that aquifer loss equals BQ and well loss equals CQ^2, then L_p would equal the well efficiency. However, testing of hundreds of wells has shown that these assumptions are not correct. Therefore, L_p is not indicative of well efficiency. For example, while turbulent flow may occur near the well and in the well screen, it may also exist in the undisturbed formation around the well. When this happens, a portion of the CQ^2 term actually comes from aquifer loss. Thus, if L_p is used as the well efficiency, a well having turbulent flow may be judged to be inefficient when it may be, in fact, quite efficient.

Conversely, in most wells a substantial portion of the well loss can be attributed to laminar flow rather than turbulent flow. Under these circumstances, part of the BQ term includes well losses rather than only aquifer losses. Thus, when L_p is used as the efficiency value, it appears that a well, which has little or no turbulent flow, is judged to be efficient, when the true efficiency may be quite low. Section 8.1.5 includes a method for calculating well efficiency.

8.1.5 Areal Aquifer Test Interpretation

The analytical methods described in the previous sections are based upon theoretical behavior of ground water under idealized conditions and in conformance with the assumptions stated in Section 8.1.3.1.

Unfortunately, the complexity of geologic systems virtually ensure that the assumptions necessary for exact application of the methods discussed will functionally never be found in natural conditions.

As a result, the data plots derived from field testing programs will commonly contain anomalies, which introduce uncertainty into the validity of the interpretation of the data.

For that reason, a thorough understanding of the geologic framework of the test site must be incorporated into test design, as well as data analysis and interpretation.

Some patterns of data plots are highly suggestive of certain sets of hydrogeologic or well construction parameters. This section includes some of the more common graph patterns with brief discussions of the most probable mechanisms generating the hydrodynamic behavior involved. Most interpretations will be based upon Jacob-Cooper analysis for ease of illustration of effects.

- **Delayed Drainage Effects**

  In settings where either stratigraphic variability is high or the aquifer materials are fine-grained, the frictional resistance to vertical movement of water under the influence of gravity is high. Therefore, the data plots for water table behavior reflect an earlier steep gradient followed by flattening and subsequent steepening of the data plot (see Figure 8-16).

  This situation requires extended pumping duration in order to obtain valid estimates of transmissivity and storativity. Estimates based upon early portions of the time-drawdown curve will not be accurate.

  Treatment of this type of aquifer behavior is discussed by Prickett (1965) in applying Boulton (1963) type curves to analysis of the data. an empirically derived curve for estimating delayed drainage effects of various sediment types can be found in Figure 8-17.

- **Encountering Recharge/Discharge Boundaries**

  When the expansion of the cone of influence generated by a pumping well encounters a source of recharge (stream, breached aquitard, abrupt thickening of aquifer), the slope of the data plot will flatten in a semi-log plot (see Figure 8-18) or drop below the type curve plot for non-leaky artesian conditions (see Figure 8-19).

  Similarly, encountering negative or discharge boundaries (valley walls, facies change) will result in a steepened semi-log plot (see Figure 8-20) or a curve that plots above the basic type curve for non-leaky artesian conditions (see Figure 8-19).

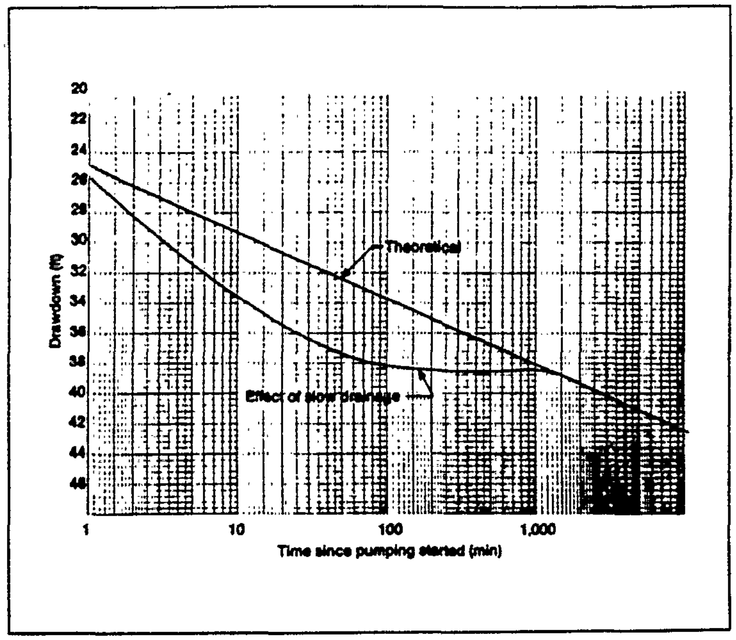


Figure 8-16 Time-drawdown curve showing the effect of slow drainage on the early part of the curve.
(After Driscoll, 1986)

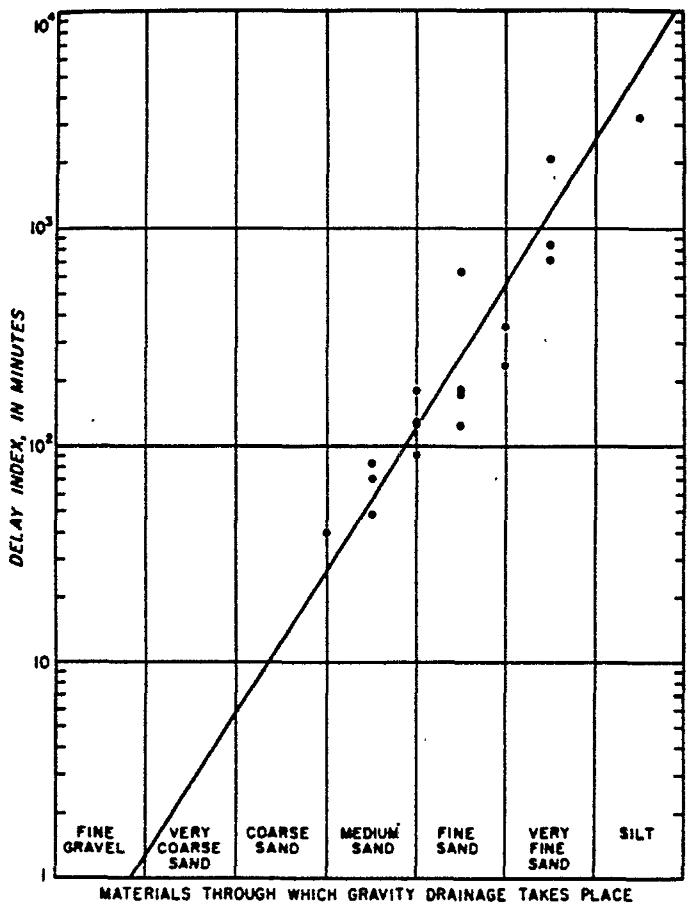


Fig. 8-17 Curve for estimating the time at which the effects of delayed gravity drainage cease to influence drawdown. (*From Prickett, 1965.*)

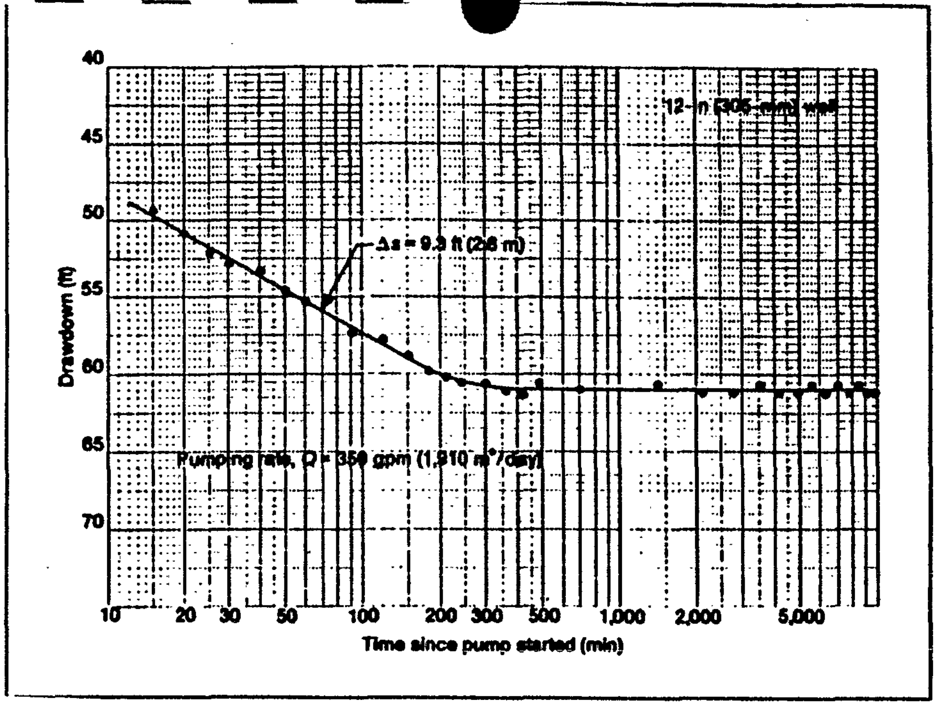
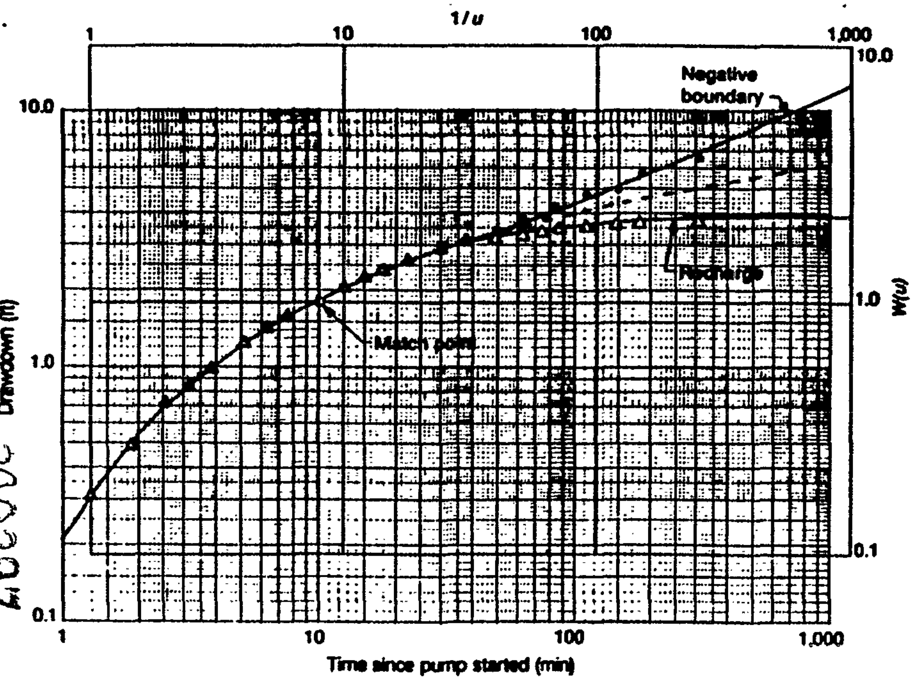


Figure 8-18 When recharge to the aquifer occurs within the zone of influence of the well, the slope of the time-drawdown curve becomes flatter. The horizontal leg indicates that recharge equals well discharge after 240 minutes of pumping. (After Driscoll, 1986)



300297

Figure 8-19 Effect of recharge and negative boundaries on pumping test data when using the Theis curve-

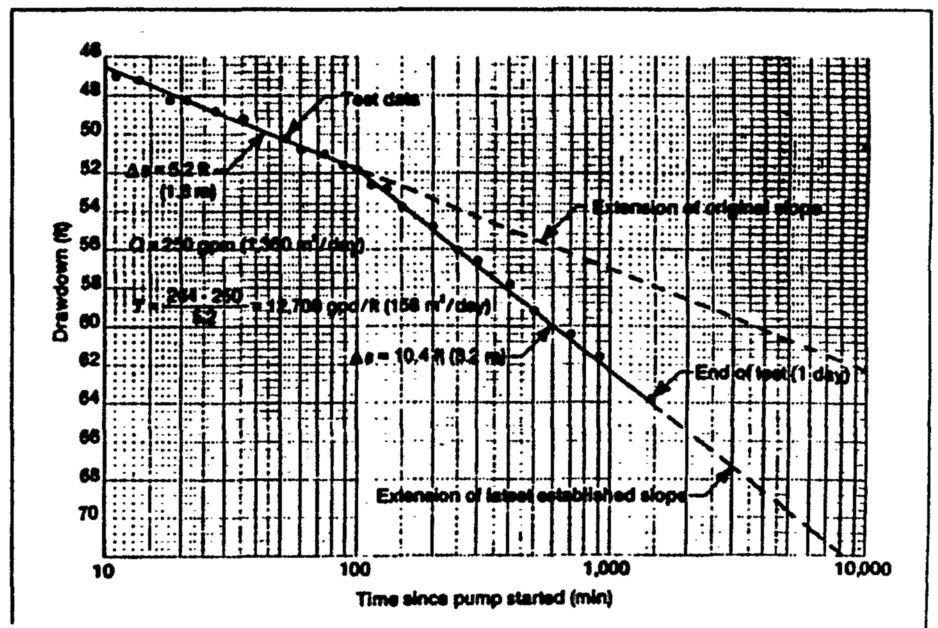


Figure 8-20 Steepening of the time-drawdown, semilog curve indicates a limited aquifer. The expanding cone of depression encountered one or more impervious boundaries at the time shown by the change in slope. (After Driscoll, 1986)

Methodology for obtaining estimates of distance to the boundary(s) is contained in Walton (1970) and Kruseman and DeRidder (1983).

- **Casing Storage**

  Many aquifer tests in hazardous waste projects will involve low rates of pumping due either to aquifer permeability characteristics or constraints on storage or disposal of produced water.

  As a result, there is a potential for significant interaction between water stored in the casing and water contributed to the well by the aquifer. This interference can produce a plot configuration similar to the one caused by encountering a recharge boundary (see Figure 8-21).

  In situations where this condition could be potentially significant, e.g., relatively large well diameter and low pumping rate, the effects of this casing storage should be calculated.

  The recommended procedure involves the following calculation based on Schafer (1978). For an example, of an 8-inch well pumping at 5.2 gpm, with Q/s = 0.132 gpm/ft with pump column diameter of 1.2 inches (see Figure 8-22):

$$t_c = \frac{0.6(d_c^{\,2} - d_p^{\,2})}{Q/s} = 0.6 \ \frac{(8)^2 - (1.2)^2}{0.132} = 284 \ \text{min.}$$

Where:

t_c = time, in minutes when casing storage effects becomes negligible

d_c = inside diameter of well casing, in inches

d_p = outside diameter of pump column, in inches

Q/s = specific capacity of the well, in gpm/ft of drawdown, at time t_c

Therefore, any portion of the data plot up to a point approximately 284 minutes into the test would be potentially affected by water stored in the casing and treated as suspect.

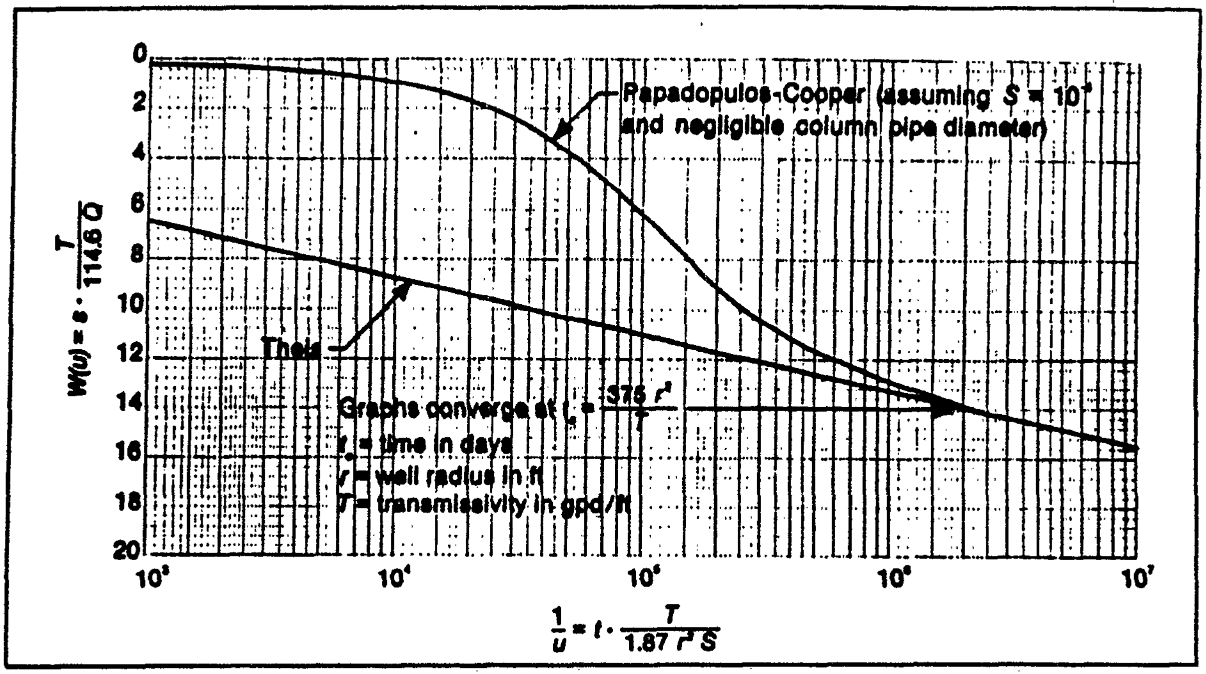


Figure 8-21 **Graphic representation of the Papadopulos-Cooper equation which takes into account casing storage.** (After Driscoll, 1986)

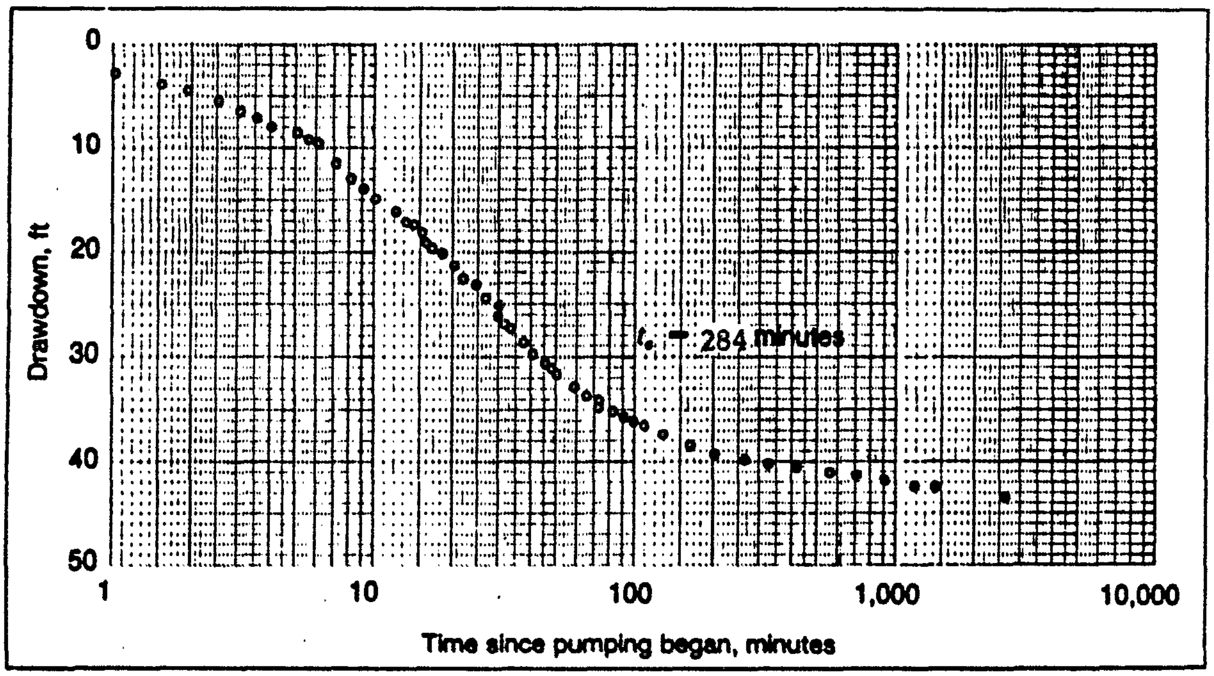


Figure 8-22 **In this drawdown curve, an apparent recharge boundary occurs about 80 minutes after pumping began. Yet no obvious recharge sources such as rivers or lakes exist nearby.**
(After Driscoll, 1986)

- **Partial Penetration Corrections**

When ground water flow is not strictly radial and when deformation of flow lines is necessary to bring water into the borehole, potentiometric head is modified around the well to a distance equal to approximately twice the thickness of the aquifer (see Figure 8-23).

The analysis of data from aquifer tests in which wells either do not fully penetrate the aquifer or where improper screening intervals are present requires the application of techniques for estimation of the effects of the distortion.

Kozeny (1933) developed an equation for estimating results from partially penetrating wells in reasonably homogenous confined aquifers.

$$\frac{Q/s_p}{Q/s} = L\left(1 + 7\sqrt{\frac{r}{2bL}\log\frac{\pi L}{2}}\right)$$

Where:

Q/s_p = specific capacity of a partially penetrating well, in gpm/ft

Q/s = maximum specific capacity of a fully penetrating well, in gpm/ft

r = well radius, in feet

b = aquifer thickness, in feet

L = well screen length as a fraction of aquifer thickness.

A family of curves representing solutions to the Kozeny Equation are illustrated in Figure 8-24 for application to confined aquifer settings.

- **Dewatering Corrections in Unconfined Aquifers for Calculating True Transmissivity**

If the saturated thickness of an unconfined aquifer decreases by more than 20 percent during pumping, drawdown data must be adjusted if the true transmissivity is to be calculated using the Jacob analysis. The non-equilibrium equation assumes that

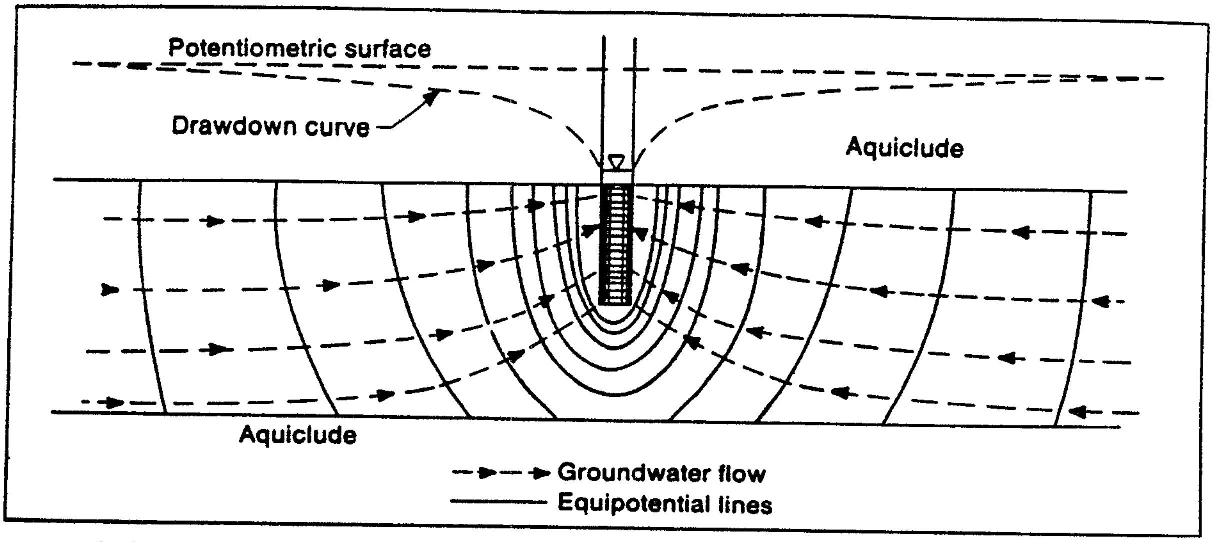


Figure 8-23**When the intake section of a well partially penetrates a confined aquifer, flow lines deviate somewhat from the radial flow pattern associated with a fully penetrating well.** *(Water and Power Resources Service, 1981).*

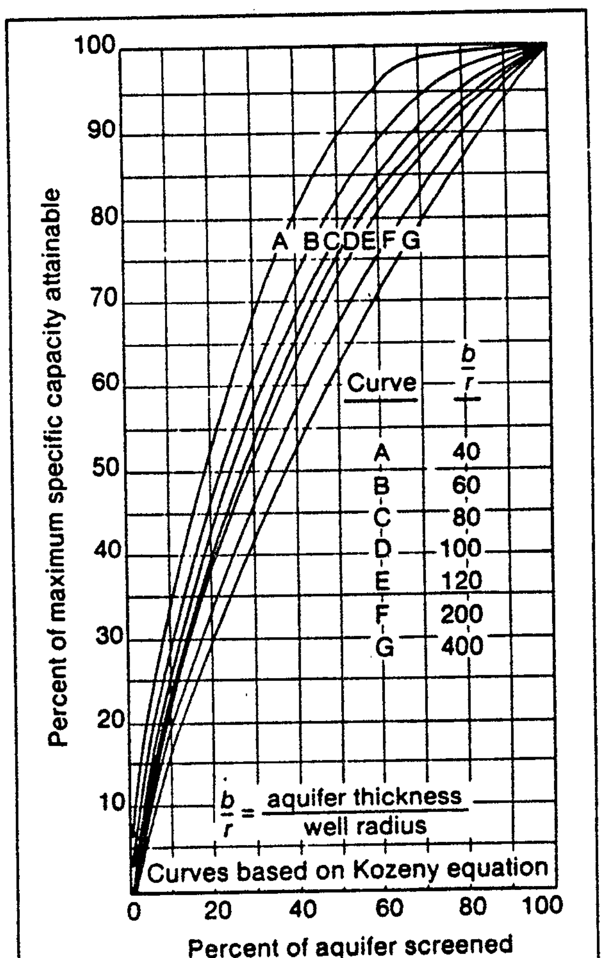


Figure 8-24**Relationship of partial penetration and attainable specific capacity for wells in homogeneous confined aquifers.**

(After Driscoll, 1986)

the aquifer thickness remains constant during pumping as in a confined aquifer. But in many shallow unconfined aquifers, the cone of depression may become large enough that a significant portion of the aquifer becomes dewatered.

As the saturated thickness decreases, the specific capacity of the well also decreases. The resulting extra drawdown reflects the actual reduction in the transmissivity of the aquifer as it becomes partially dewatered.

To obtain the true transmissivity of the aquifer (under fully saturated conditions) from the Jacob equation, the measured drawdown is adjusted by the following equation:

$$s_t = s_a - \frac{s_a^2}{2b}$$

where s_t is the drawdown adjusted to its theoretical value, s_a is the actual or measured drawdown, and b is the saturated thickness of the unconfined aquifer when no pumping is taking place. The theoretical (adjusted) drawdown will always be less than the measured drawdown.

An example will illustrate these points. Data from a constant-rate pumping test are shown in Figure 8-25. Two plots are shown: measured data and the corresponding adjusted data; the adjusted data are calculated using Equation 1. For example, if t = 90 minutes, s_a = 8.3 ft, and b = 28 ft, then S_t = 7.05 ft. The true transmissivity (T_t) is 45 percent larger than the transmissivity (T_a) calculated on the basis of drawdown data.

- **Mechanical Efficiency of Pumping Wells**

All aquifer analytical methods for estimating well performance are based upon an assumption that the well is operating at 100% mechanical efficiency. This is highly unlikely to be true for any constructed artifact.

Levels of efficiency of operation for water wells below 100% can be attributed to many different causes, the most common of which are listed below.

1. Well design parameters which depart from ideal, e.g., less than 100% screening of aquifer.

2. Incomplete development of the well with resultant drilling fluid, hole damage or other interference at the borehole-aquifer interface.

3. Over-pumping of the well beyond design parameters.

4. Well deterioration due to aquifer/screen encrustation and plugging.

5. Pumping of well to a level below main aquifer entry point producing cascading and turbulence in rock wells.

For whatever reason, most wells will vary from maximum efficiency and estimation of the present operating efficiency of the well is often useful in design and implementation of aquifer characterization and/or remedial programs.

Mogg (1968) defined well efficiency as the ratio of the actual specific capacity at the designed well yield after 24 hours of continuous pumping to the maximum specific capacity possible, calculated from formation characteristics and well geometry. In this method of defining efficiency, it is possible to identify how much of the total head loss is attributable to natural losses in the formation and those caused by well construction damage to the aquifer and the installation of a screen and filter pack. A procedure for calculating well efficiency is as follows:

1. Graph the time drawdown data on semi-log paper.

2. Calculate Δs.

3. At a particular time, note the drawdown in an observation well.

4. On a distance-drawdown graph, plot the drawdown for the observation well (for the particular time) at the proper distance from the pumping well.

5. Complete the drawdown curve by using a slope of 2 times Δs (in the Jacob equation, $\log r^2 = 2 \log r$, so the value of Δs in the distance-drawdown graph is twice the value of Δs in the time-drawdown graph).

6. Extend the slope of the data to the radius of the well.

7. In a 100-percent efficient well, drawdown just outside the borehole should equal the drawdown inside the well. It is more likely, however, that the water level inside the well is lower. Therefore, efficiency equals drawdown outside the borehole divided by drawdown inside the casing, times 100.

8. An efficiency of 70 to 80 percent is usually obtainable if good design, construction, and development practices are followed.

   An example of the efficiency calculation is shown in Figure 8-26.

8.2 In-Situ Permeability Testing

Methods of estimating in-situ permeability are divided into the following three major types:

- Falling Head Tests are applicable to soil zones above and below the water table.
- Rising Head Tests are only applicable to aquifer zones below the water table.
- Constant Head Tests are applicable to aquifer zones above and below the water table.

8.2.1 Design and Field Procedures for Variable Head Tests

Falling head and rising head tests can be descriptively combined for field operations as variable head tests. These tests are utilized in situations where non-equilibrium methods and analyses are appropriate.

The applications of these procedures are referred to as "slug" tests and involve the raising or the lowering of the water table by a method to produce an imbalance in the system. Measurements of the behavior of the system as it returns to equilibrium are then made and used for analysis.

8.2.1.1 Test Hole Preparation

Select a borehole size that will allow the variable head test to be performed in a reasonable length of time. It is desirable to run the test to 90 percent equalization (i.e., until 90 percent of the differential head created by bailing or adding water is dissipated) (Hvorslev, 1951). A table of 90 percent equalization time for various borehole dimensions

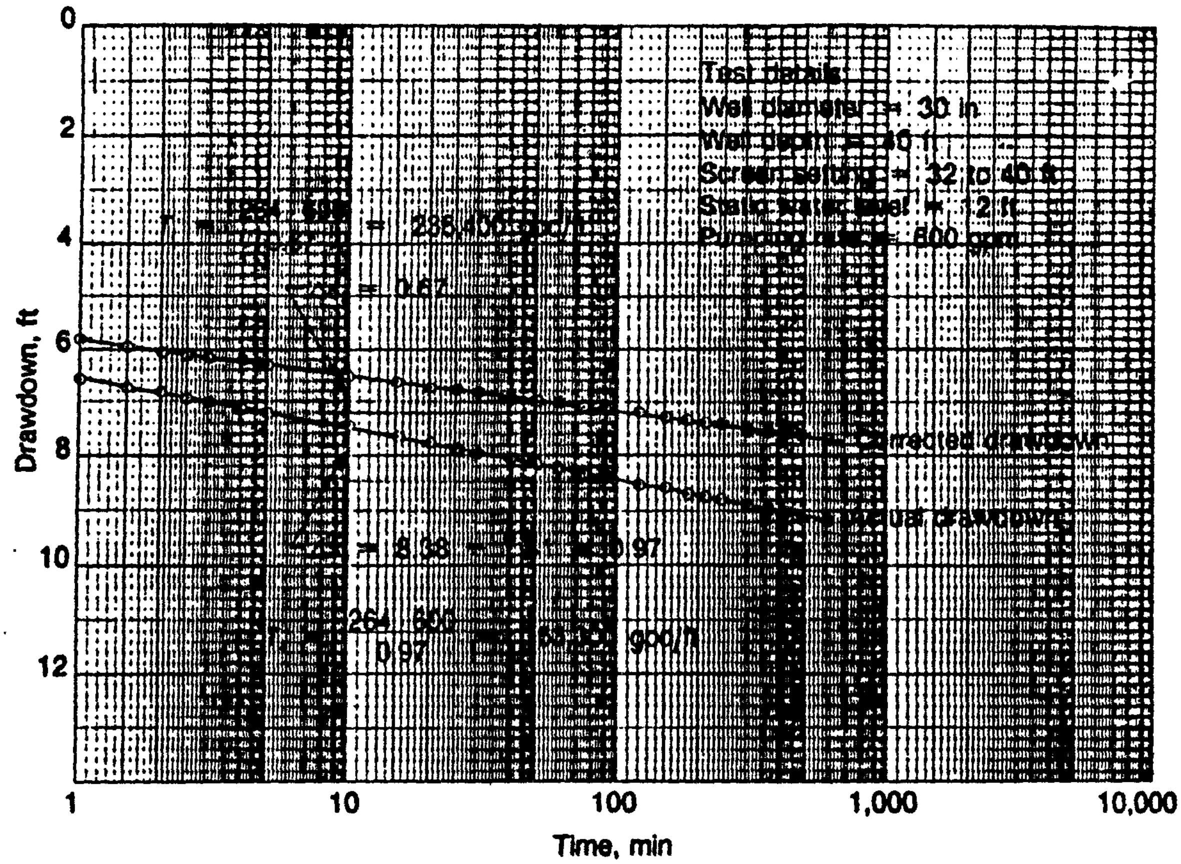


Figure 8-25 **Plot of measured drawdown and adjusted drawdown from a constant-rate pumping test.**
(After Driscoll, 1986)

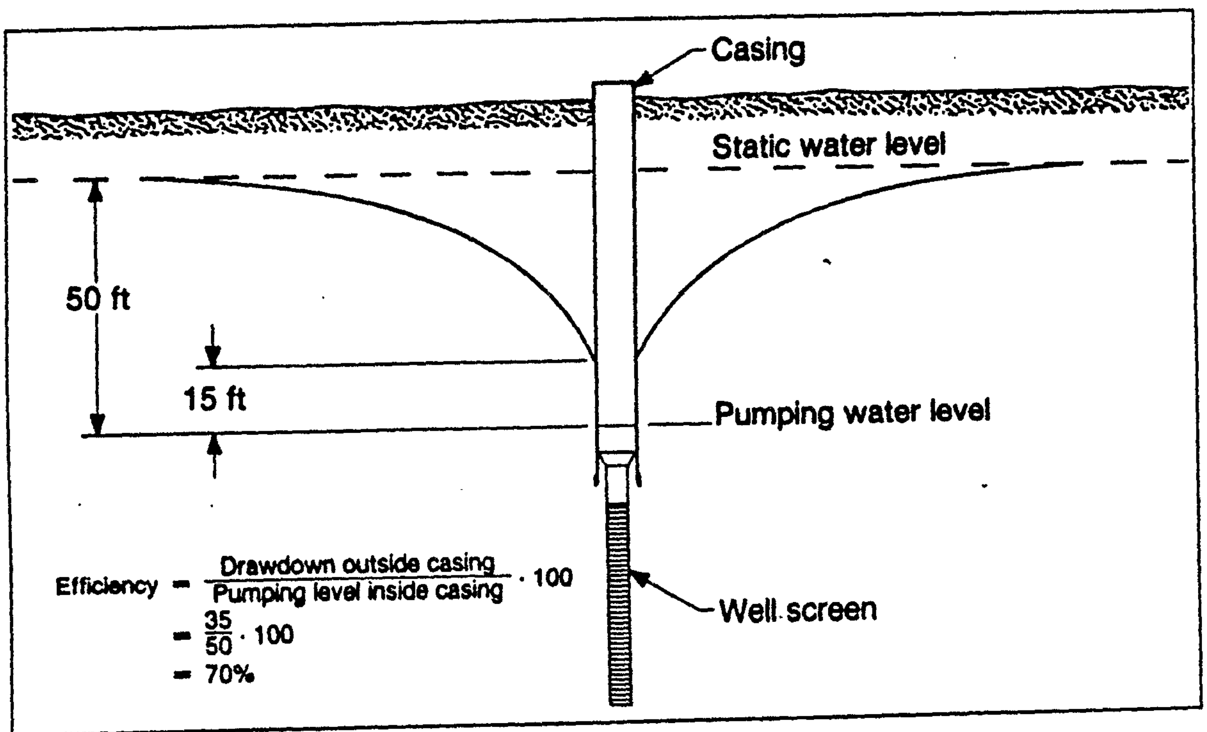


Figure 8-26 **Calculating true well efficiency for a high-capacity well.**
(After Driscoll, 1986)

is provided in Figure 8-27, as well as the method to compute the time to 90 percent equalization for any borehole diameter.

If the test is run in a piezometer, the filter length of the piezometer should be sufficiently long to provide a representative value of permeability within a 24-hour test period (Tabor) or longer. The test section length in boreholes should be about 5 feet (USBR, G-97) with the borehole cased above the test interval. The analysis becomes less accurate if the entire borehole is uncased.

Various types of borehole designs can be used. The most common types are listed below, in order of their decreasing desirability (see Figures 8-28 through 8-33).

Falling Head Test

F: Standpipe Piezometer
(very low permeability materials only) (Figure 8-33)

D: Perforated Casing over Test Section, Cased Above (Figure 8-30)

E: Fully Cased Borehole open only at base
(very high permeability materials only) (Figure 8-32)

C: Gravel-filled Test Section, Cased Above (Figure 8-31)

B: Unlined Test Section, Cased Above (Figure 8-29)

Rising Head Test

D: Perforated casing over Test Section, Cased Above (Figure 8-30)

C: Gravel-filled Test Section, Cased Above (Figure 8-31)

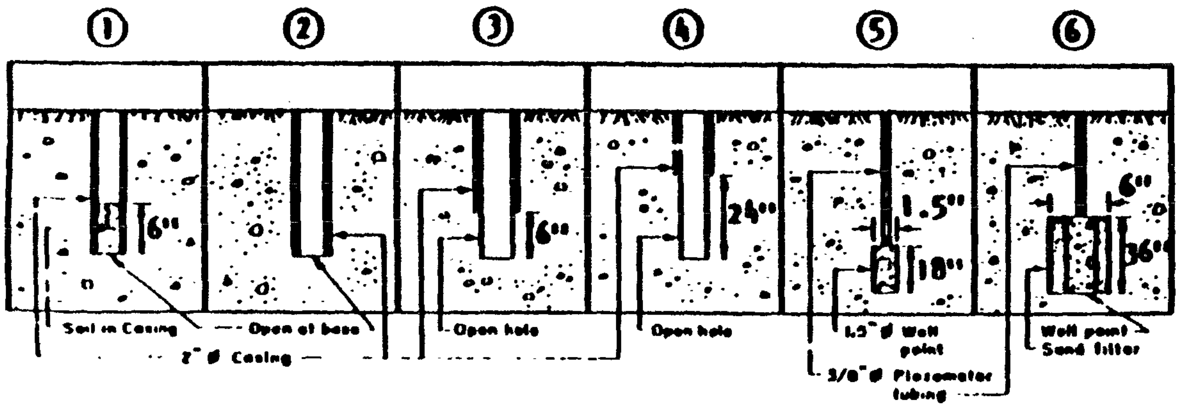
B: Unlined Test Section, Cased Above (Figure 8-29)

8.2.1.2 Test Procedures

Falling Head Test

1. Prepare borehole as previously described.
2. If possible, bail a small amount of ground water and record its temperature.
3. Record the temperature of the water that will be added.

TIME FOR 90 PERCENT EQUALIZATION = T_{90} (m = minutes, h = hours, d = days)										
APPROXIMATE SOIL TYPE	SAND			SILT			CLAY			
COEFFICIENT OF PERMEABILITY IN CM/SEC	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
1 2-IN. CASING - SOIL IN CASING, L = 3D = 6-IN.	6^m	1^h	10^h	4.2^d						
2 2-IN. CASING + SOIL FLUSH BOTTOM CASING	0.6^m	6^m	1^h	10^h	4.2^d					
3 2-IN. CASING - HOLE EXTENDED, L = 3D = 6-IN.		1.5^m	15^m	2.5^h	25^h	10^d				
4 2-IN. CASING - HOLE EXTENDED, L=12D=24-IN.			6^m	1^h	10^h	4.2^d	42^d			
5 3/8-IN. PIEZOMETER WITH WELL POINT DIAMETER 1½-IN, LENGTH 18-IN.				3^m	30^m	5^h	50^h	21^d		
6 3/8-IN. PIEZOMETER WITH WELL POINT AND SAND FILTER, D = 6-IN., L = 36-IN.					12^m	2^h	20^h	8.3^d	83^d	



NOTE:

The time to 90% equalization can be estimated for a soil/rock mass as follows; $T_{90} = 2 \cdot 3 \cdot \frac{A}{F \cdot k}$ where

A is the cross-sectional area of the standpipe/borehole

k is the estimated permeability

F is the shape factor (Hvorslev) shown on Figures 8-2 and 8-3

Figure 8-27 **TIME TO 90% EQUALIZATION**
(after Hvorslev 1951)

300307

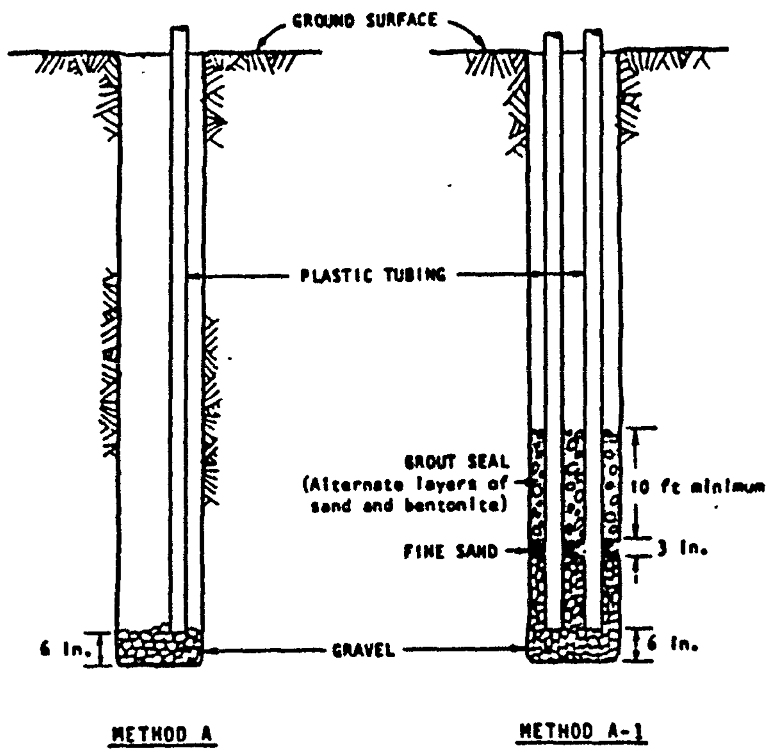


Figure 8-28 BOREHOLE PREPARATION: UNLINED BOREHOLE

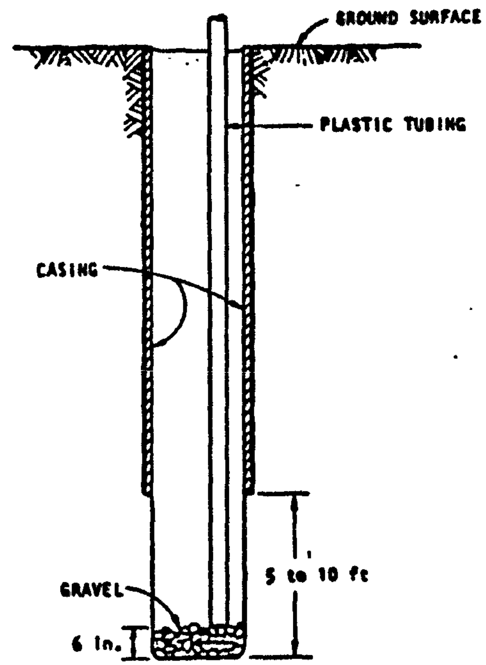


Figure 8-29 BOREHOLE PREPARATION METHOD B: UNLINED TEST SECTION, CASED ABOVE

300308

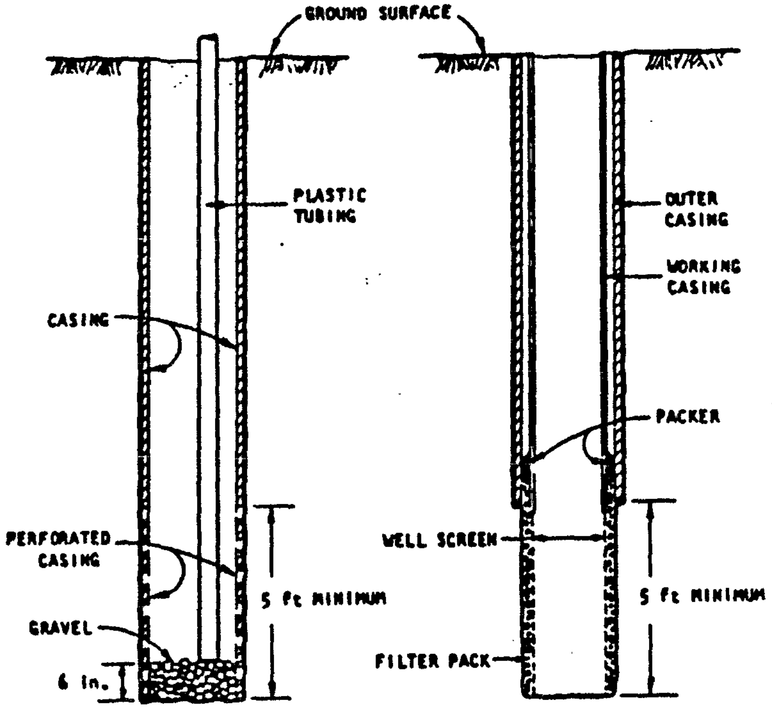


Figure 8-30 BOREHOLE PREPARATION METHOD D: PERFORATED CASING OVER TEST LENGTH, CASED ABOVE

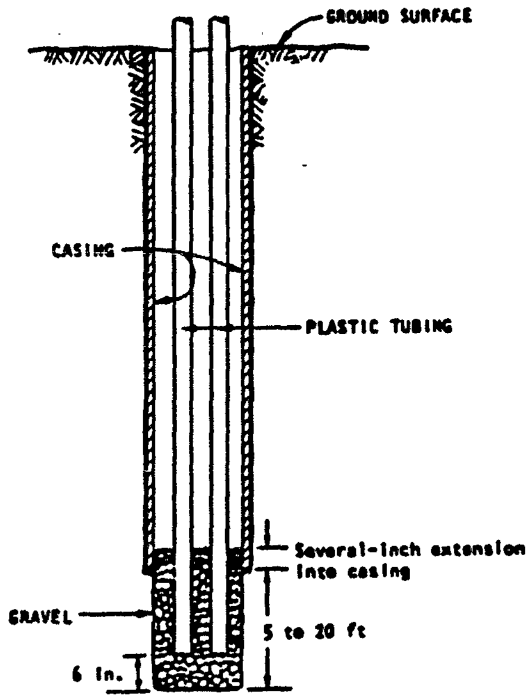


Figure 8-31 BOREHOLE PREPARATION METHOD C: GRAVEL-FILLED TEST SECTION, CASED ABOVE

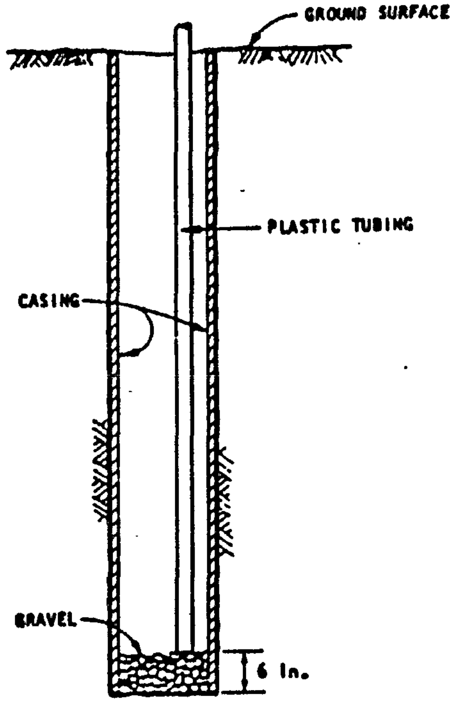


Figure 8-32 BOREHOLE PREPARATION METHOD E: FULLY-CASED BOREHOLE, OPEN AT BOTTOM ONLY
(After WCC, 1977)

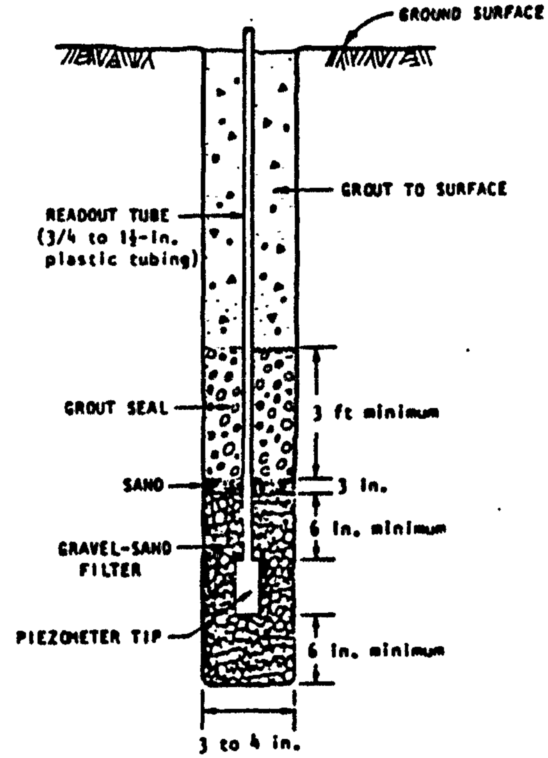


Figure 8-33 BOREHOLE PREPARATION METHOD F: PIEZOMETER INSTALLATION
(After WCC, 1977)

300310

4. Fill the borehole/piezometer to the top with clean water. In highly permeable material, the water level should be raised as high as practical.

5. If a pressure transducer array is not available, then use an electric probe and read the depth to water from the top of the casing. After each reading, withdraw and dry the tip of the level indicator.

   Read the depth to water:

   - At 30 sec intervals for 5 min;
   - Then at 1 min intervals for 10 min; and
   - Then at 5 to 10 min (or longer) intervals depending on the rate of fall for the remainder of the test and the estimated value of T_{90}.

   Record the data until 90 percent of the excess head has dissipated. The time required for 90 percent equalization is a function of soil/rock permeability and borehole geometry and may vary from a few minutes to several days. Generally though, an hour should be allowed for each test (Dixon and Clark, 1975). A table of 90 percent equalization times is presented in Figure 8-27.

6. Record the data on the data sheet in Figure 8-34.

<u>Rising Head Test</u>

1. Prepare the borehole as prescribed above.

2. Lower the water level in the borehole by bailing, by dewatering with a compressor air line, or by pump when the total suction lift is not more than about 15 feet.

3. Using an electric probe or pressure transducer, read the depth to water from the top of the casing. After each reading draw and dry the top of the level indicator.

   Reading the depth to water:

   - At 30 sec intervals for 5 min;
   - Then at 1 min intervals for 10 min; and
   - Then at 5 to 10 min intervals depending on the rate of rise for the remainder of the test and the estimated value of T_{90}.

Location: ______________________ Name: ____________________________

Borehole No: ____________________

Date of Test: ____________________

Elevation of Base of Test Section: ____________________

Elevation of Top of Test Section: ____________________

ELAPSED TIME	Depth to Water from Top of Casing : y	Excess Head : H
t = 3.5 min		
t = 4.0 min		
t = 4.5 min		
t = 5.0 min		
t = 6.0 min		
t = 7.0 min		
t = 8.0 min		
t = 9.0 min		
t = 10.0 min		
t = 11.0 min		
t = 12.0 min		
t = 13.0 min		
t = 14.0 min		
t = 15.0 min		
t = 20.0 min		
t = 25 min		
t = 30 min		
t = 35 min		
t = 40 min		
t = 45 min		
t = 50 min		
t = 55 min		
t = 60 min		

Figure 8-34 VARIABLE HEAD TEST DATA SHEET (CONTINUED)
(after WCC, 1977)

Location: ____________ Name: ____________

Borehole No: ____________ G.W. Elevation before Test: ________

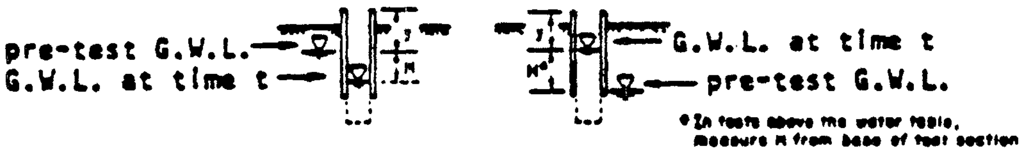
Date of Test: ____________ Type of Test (Falling/Rising): ______

Ground Elevation: ____________ G.W. Temperature ___ °F Added Water ___ °F

DIMENSIONS OF

Borehole	or Piezometer
Depth of BH before test ________	Depth of Top of Filter ________
Depth of BH after test ________	Depth to Bottom of Filter ________
Depth of Unperforated Casing ________	Length of Filter Section ________
Length of Test Section below Casing (May be "0") ________	Diam. of Filter Section ________
	Piezometer Type ________
Diam. of Test Section ________	Depth to Top of Piez. ________
Height of Casing above G.L. ________	Depth to Base of Piez. ________
Test Section: ☐ Unlined ☐ Well Screen ☐ Open at Bottom Only	Outside Diam. of Piez. ________
	Inside Diam. of Piez. ________
Inside Diam of Unperforated Casing ________	Inside Diam. of Tubing above Piez. ____
	Height of Tubing above G. L. ________

Below G.L. (first three borehole items); Below G.L. (Depth of Top of Filter, Depth to Bottom of Filter); Below G.L. (Depth to Top of Piez., Depth to Base of Piez.)



RISING HEAD TEST   FALLING HEAD TEST

ELAPSED TIME	Depth to Water from Top of Casing : y	Excess Head : H
t = 0		H_0 =
t = 30 sec		
t = 1 min		
t = 1.5 min		
t = 2 min		
t = 2.5 min		
t = 3.0 min		

(continued)

300313

Figure 8-34 VARIABLE HEAD TEST DATA SHEET
(After WCC, 1977)

Record the data until 90 percent of the excess head has dissipated. The time required for the 90 percent equalization is a function of soil/rock permeability and borehole geometry and may vary from a few minutes to several days. Generally though, an hour should be allowed or each test (Dixon and Clark, 1975). A table of 90 percent equalization time is displayed in Figure 8-27.

4. Record the data on the data sheet shown in Figure 8-34.

8.2.2 Selected Analytical Procedures for Data from Variable Head Tests

Although numerous authors have developed methods for analyzing data from variable head tests, the following techniques are considered to be the most commonly used and will be discussed in this memorandum.

8.2.2.1 Unsaturated Zone

For tests in the unsaturated zone, Schmid (1967) has presented a solution for a fully cased well open at the bottom. It is a purely calculated value and should be considered as providing only a very rough approximation of permeability.

The procedure for analyzing falling head data from the unsaturated zone is as follows:

1. Assume that the degree of saturation in the zone wetted by the test is S = 0.85. It may be desirable to test the sensitivity of the calculated permeability to a range of S from 0.75 to 0.95.

2. Estimate the porosity $n = V_v/V$ where V_v = volume of voids and V = total volume of a rock/soil sample.

3. At any time t_i, the height of water in the borehole is H_i measured from the bottom of the well. Select any two data points H_1, t_1, and H2, t_2.

4. Calculate $$K=\frac{R}{4}\;\frac{\ln(H_1/H_2)}{T_2\left[\frac{3(H_1-H_2)}{4S_nR}+1\right]^{1/3}-t_1}$$

Where:

R = the interior radius of the cased borehole
n = the porosity
H_i = height of water in the borehole at time, t_i
S = final degree of saturation in zone wetted by test

8.2.2.2 Saturated Zone

Three methods are traditionally used in analyzing data from the saturated zone. The classical procedure developed by Hvorslev (1951) makes the following assumptions.

1. The soil is saturated, and gas is not present in the system.
2. Ground water level is undisturbed and constant or predictable with time.
3. The soil and water are incompressible.
4. The shape factor is constant throughout the test.
5. The aquifer is infinite in vertical extent.
6. The soil is homogenous and isotropic.
7. The well fully penetrates the aquifer.

Estimation of aquifer parameters using the Hvorslev (1951) method involves the following equation:

$$K = \frac{R_c^2 \ln(L/r_c)}{2\ L\ T_o}$$

Where:

K = hydraulic conductivity
r_c = radius of well casing
L = length of screened or saturated interval
T_o = basic time lag

The time lag T_o is the time that would be required for the complete recovery of the well if the original rate of inflow was maintained. It is calculated by plotting H/Ho versus time on a semi-log plot, with H/Ho being the logarithmic scale. H is the residual drawdown at a given time and Ho is the initial drawdown at time $t = 0$. T_o is derived by reading the time at which H/Ho = 0.37. The 0.37 value is controlled by the "shape factor", and varies for different piezometer configurations and permeability ratios (see Figure 8-35).

DEFINITION OF SYMBOLS

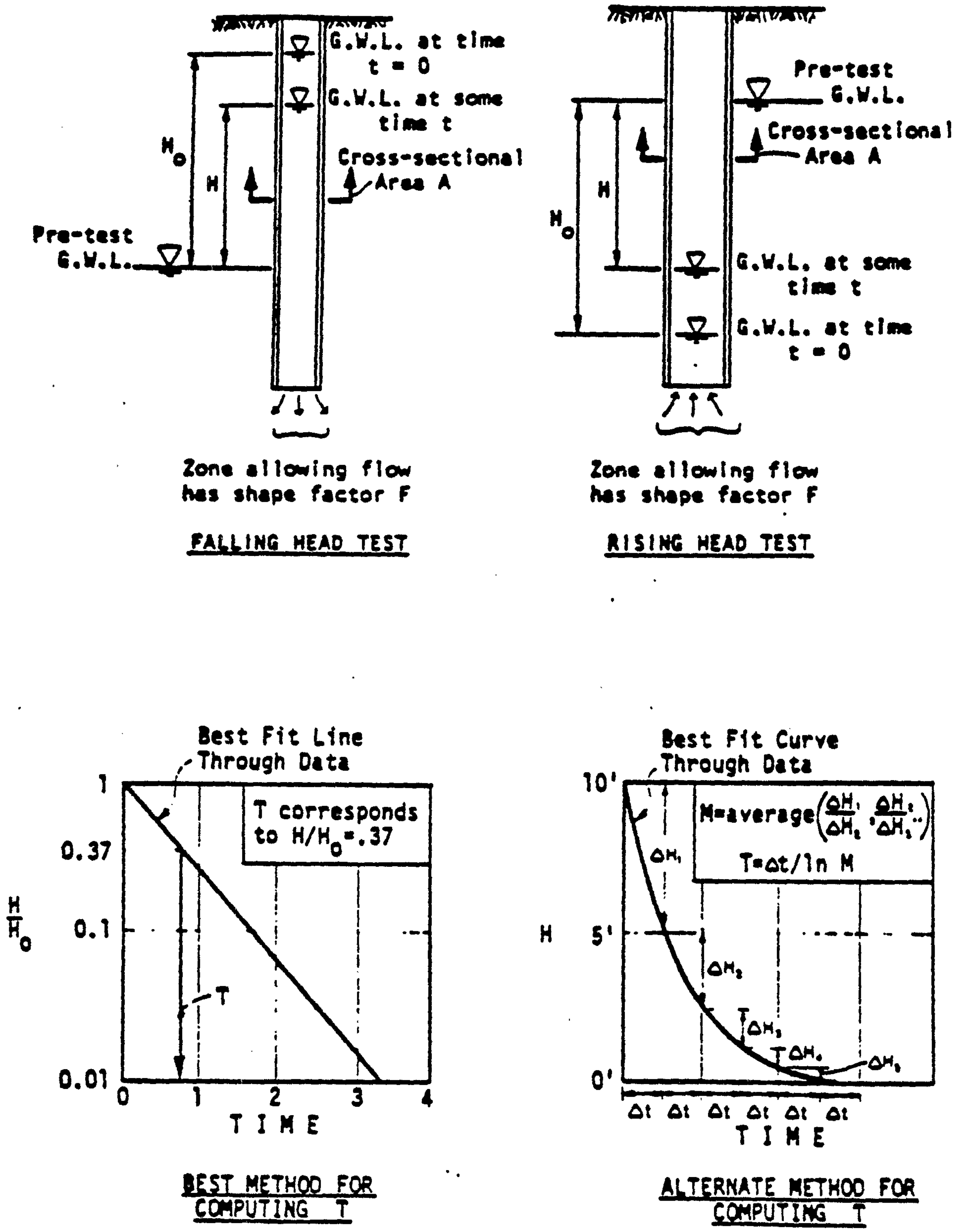


Figure 8-35 CALCULATION OF BASIC TIME LAG, T, FOR VARIABLE HEAD TESTS
(Hvorslev, 1951)

The "shape factor" is based upon the following conditions:

1. Whether the well is screened through the entire interval or is just open at the base.
2. The well completion details.
3. Whether the well is set in unconfined conditions.
4. Permeability ratios (vertical vs. horizontal) for the aquifer and the gravel pack (see Figure 8-36).

When the soil/rock mass is anisotropic, the engineer must estimate the ratio of horizontal to vertical permeability $K_h/k_v = m^2$ or calculate it from the laboratory tests. The value of m is then introduced into the computation of the shape factor F, as shown in Figure 8-36. The error in the permeability calculations is due to an error in selection of m and generally less than the inherent error in variable head tests.

When a gravel filter is placed in the casing, the engineer must also estimate n = k'v/kv where k'v is the vertical permeability of the filter material and k_v is the vertical permeability of the soil/rock mass. Then "n" is introduced into the computation of the shape factor F, as shown in Figure 8-36.

Bouwer and Rice (1976) have developed a procedure that considers the effects from partially penetrating wells, the radius of the gravel pack, and the effective radius of influence of the test.

The Bouwer and Rice method entails solving the following equation:

$$K = \frac{r_c 2 \ \ln \ (Re/Rw)}{2Lt} \ln \frac{Yo}{Yt}$$

Where:

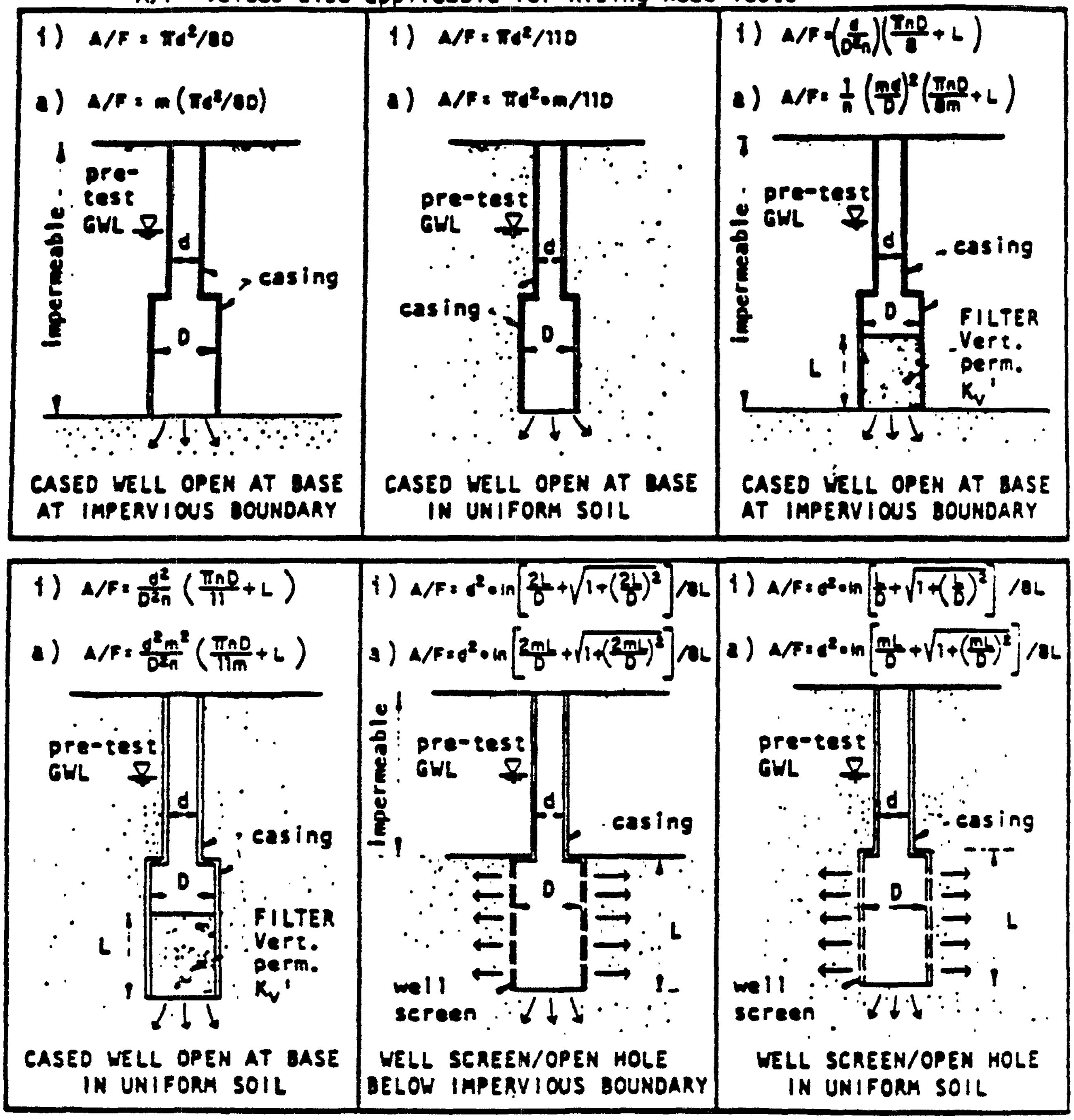
K = hydraulic conductivity
r_c = radius of well casing
Re = effective radius of influence
Rw = radius of boring
L = length of screen or saturated thickness if entire screen is not saturated
t = selected time from time/drawdown semi-log plot
Yo = initial drawdown at time t = 0
Yt = drawdown at time t

i = isotropic conditions: $K_h = K_v = K$

a = anisotropic conditions: $K_h \neq K_v$

$$K \text{ or } K_h = \frac{A}{(F \cdot T)}$$

__NOTE:__ Flow direction shown for Falling Head Tests for clarity; "A/F" values also applicable for Rising Head Tests



__DEFINITIONS:__ $K_m = \sqrt{K_v \; K_h}$; $m = \sqrt{K_h/K_v}$; $n = K_v'/K_v$

where K_v = vertical permeability of soil/rock mass

K_h = horizontal permeability of soil/rock mass

K_v' = vertical permeability of filter in casing

T is termed the basic time lag. See text for best method to determine representative value of T

300318

Figure 8-36 SHAPE FACTORS FOR VARIABLE HEAD TESTS BELOW THE WATER TABLE (Hvorslev, 1951)

The term Re/Rw is solved by the following equation:

$$\text{Ln}\ \ Re/Rw = \left[\frac{1.1}{\ln\ (H/Rw)} + \frac{A + B\ \ \ln\ [(D-H)/R_w]}{(L/R_w)} \right]^{-1}$$

Where:

H = distance from base of well to Static Water Level (SWL)
L = length of screen (or saturated thickness if entire screen is not saturated)
D = thickness of aquifer
A = constant based on value of L/Rw (see Figure 8-37)
B = constant based on value of L/rw (see Figure 8-37)

The test data are plotted on a semi-log diagram of drawdown Y_t versus time with Y_t being logarithmic. The data should generate a straight line, although a flat "tail" is frequently observed. The previous time data are used to plot a straight line, and a drawdown Yt is recorded for a selected time (t). Ty and t are used to solve the equation for K.

The Bouwer and Rice method makes the following assumptions:

1. The aquifer is of constant thickness.

2. The soil is homogenous and isotropic.

3. Flow is horizontal in the aquifer.

An additional assumption is necessary to apply the method to a confined aquifer.

4. The water enters the aquifer from the upper confining unit through compression or leakage

These assumptions are judged to be generally reasonable, recognizing that variations in aquifer thickness and anisotropic conditions will have an influence on analytical results.

An example of using the method is found below see Figures 8-38 and 8-39).

Cooper, Bredehoeft, and Papadapoulas (1967) developed a set of type curves for estimation of the transmissivity of a confined aquifer after injection or withdrawal of a known volume of water.

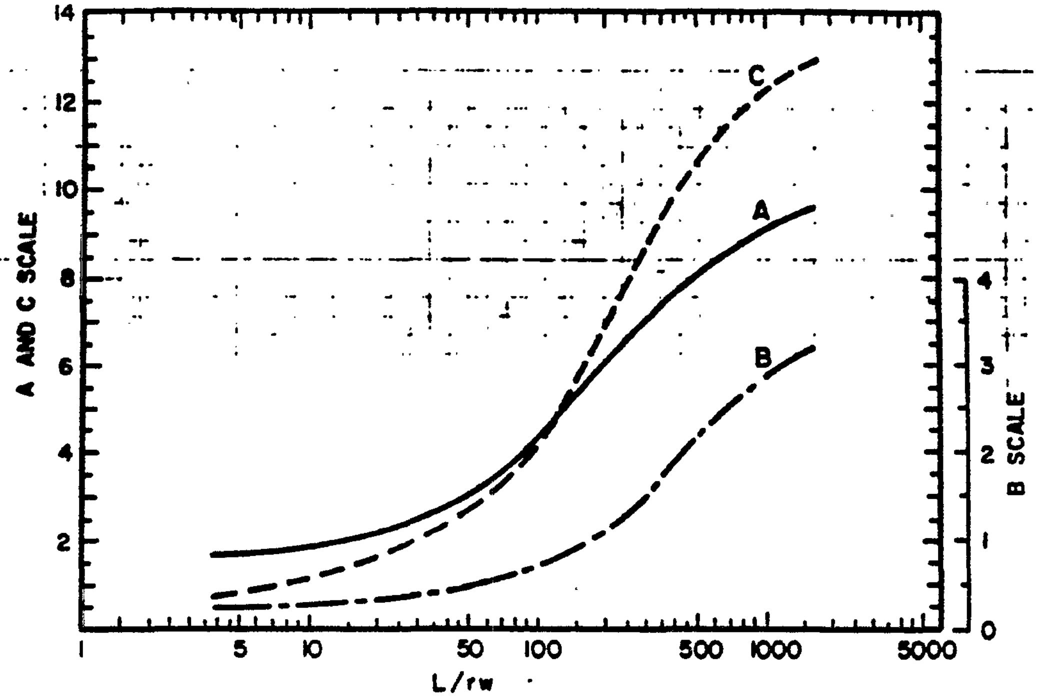


Figure 8-37
(FROM BOUWER AND RICE: GROUNDWATER HYDRAULICS, 1976)

Job No. : 21507-21525	BOUWER AND RICE COEFFECIENT A, B AND C CURVES
Prepared by: K.A.M.	
Date: 12/17/86	

Figure 8-38

EXAMPLE OF ANALYSIS OF SLUG TEST DATA
FOR AN UNCONFINED AQUIFER
After Bower and Rice (1976)

1) Slug Test Data for Example Well

r_w = 0.333 ft
r_c = 0.167 ft
L_c = 10.0 ft
D = 27.8 ft
H = 11.8 ft

y_t = 1.21 ft at t = 300 sec
y_o = 1.67 feet

2) Evaluate Coefficients A and B or C as required (Figure 3 of Bouwer and Rice, 1976)

$$L/r_w = \frac{10 \text{ ft}}{.333 \text{ ft}} = 30.03$$

A = 2.5   B = 0.38   C = ____ (C is not determined because D $\neq$ H)

3) Evaluate ln (R_e/r_w) where R_e is the effective radius over which the heads are dissipated.

$\ln\ [(D-H)/r_w] = 3.84$:   if ln [ ] $>$ 6, then = 6

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln(H/r_w)} + \frac{A + B \ln[(D-H)/r_w]}{(L/r_w)}\right]^{-1} \text{ (where } D \neq H)$$

Or,

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln(H/r_w)} + \frac{C}{(L/r_w)}\right]^{-1} \text{ (where } D = H)$$

Using the slug test data,

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln\left(\frac{11.8}{.333}\right)} + \frac{2.5 + (0.38 \times 3.87)}{30.03}\right]^{-1}$$

$$= 2.27$$

Figure 8-38 (continued)

EXAMPLE OF ANALYSIS OF SLUG TEST DATA
FOR AN UNCONFINED AQUIFER
After Bower and Rice (1976)

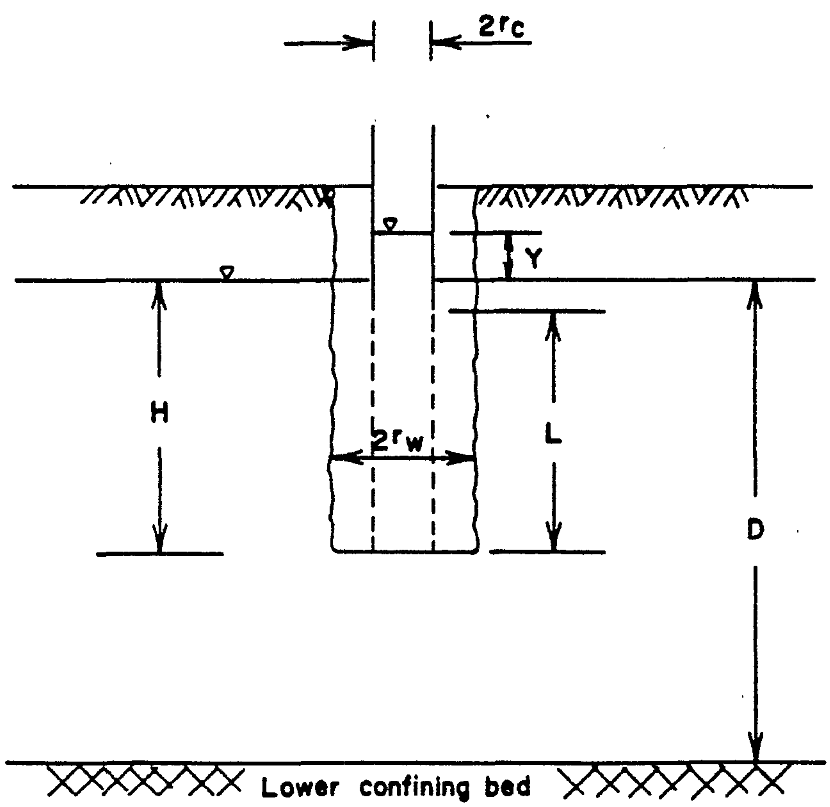
4) Evaluate the Hydraulic Conductivity, K

$$K = \frac{r_c^2 \ln\left(\frac{r_c}{r_w}\right)}{2\,Lt} \ln \frac{y_o}{y_t}$$

$$= 3.4 \times 10^{-5} \text{ ft/sec} = 1.0 \times 10^{-4} \text{ cm/sec} = 2.2 \text{ gpd/ft}^2$$

5) Evaluate the Transmissivity, T

T = KxD = 61 gpd/ft



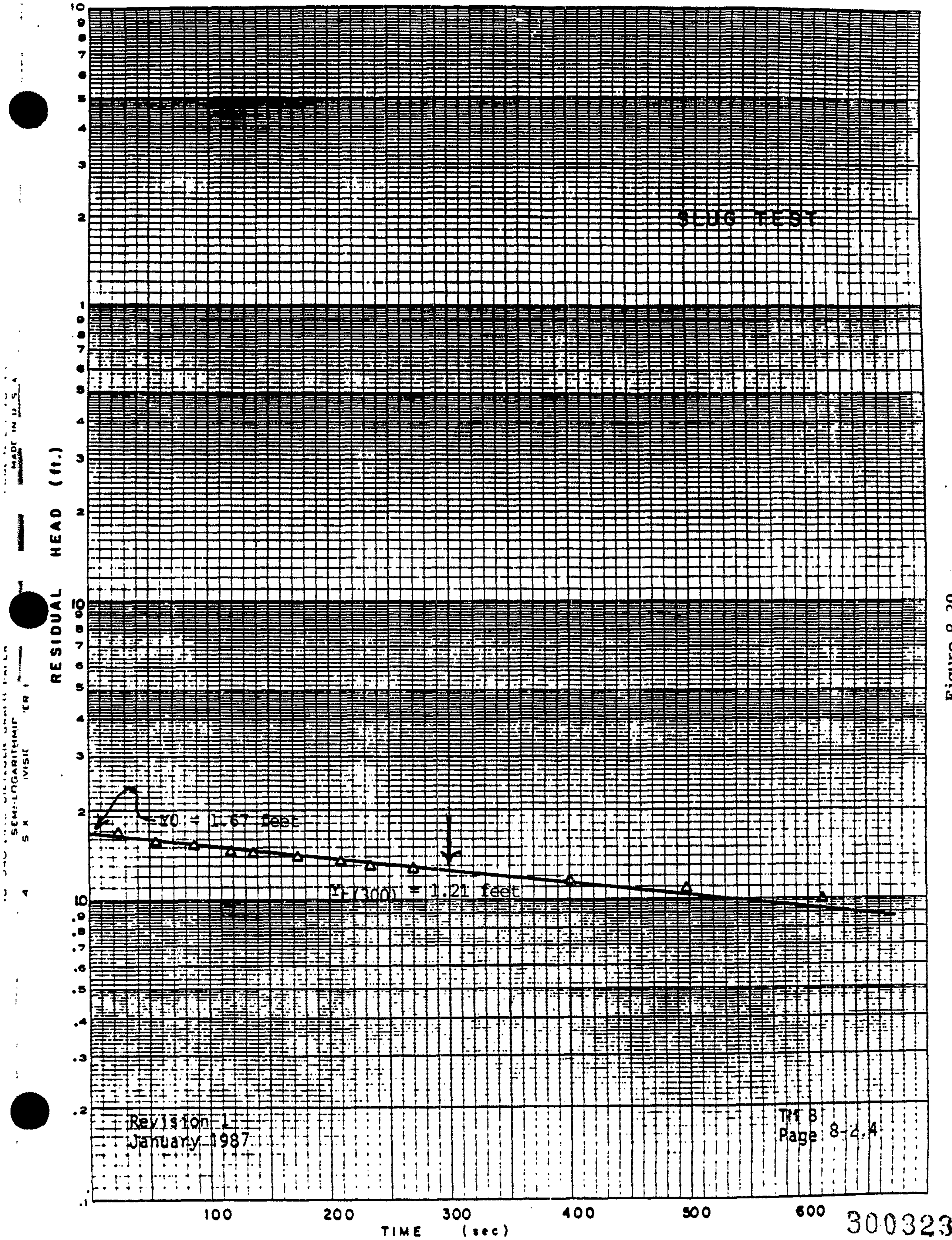


Figure 8-39
Data Plot for Bouwer /Rice Example Analysis

The field data are plotted as a dimensionless head (arithmetic scale) versus time (logarithmic scale) on semi-log graph paper and matched to a set of type curves in a procedure similar to that described for Theis curve matching in pump test analysis.

The type curves are developed by plotting H/Ho versus Tt/r_C^2 for values of:

$$\alpha = r_s^2 / r_c^2 S.$$

Where:

T = transmissivity
t = time since instantaneous head change in well (in seconds)
r_S = radius of well screen or open hole
r_C = radius of well casing
H = initial head of aquifer
Ho = head immediately after instantaneous head change
S = storativity

Calculation of the Transmissivity and Permeability is then performed by using the following equations:

$$T = \frac{\frac{Tt}{r_c^2}\,(r_c)^2}{t}; \quad K = \frac{T}{L}\ (30.48)$$

Where:

Tt/r_C^2 is determined from the graphic plot at time value t.
K = permeability; 30.48 = Conversion Factor to cm/sec
L = screen length

The procedure for calculating the values of T and the data plots necessary are illustrated in Figures 8-40 through 8-42. The type curves derived by Cooper, et al. are presented in Figures 8-43.

8.3 Constant Head and Constant Flow Tests

Sometimes it is necessary to discriminate vertical permeability variations within a borehole. This can be identified through test programs where injection of water into the zone of interest is maintained at a constant rate or constant pressure throughout the test.

Figure 8-40

EXAMPLE OF ANALYSIS OF SLUG TEST DATA FOR A CONFINED AQUIFER AFTER COOPER, BREDEHOEFT AND PAPADOPULOS (1967)

SLUG TEST MW-20

From Recorder Chart

Time (sec)	mv x 0.556 =	Head (ft)	H/Ho
30	2.7	1.50	0.94
60	2.5	1.39	0.87
120	2.2	1.22	0.76
180	1.9	1.06	0.66
330	1.4	0.78	0.49
480	1.0	0.56	0.35
630	0.7	0.39	0.24

From 2-Cycle Semi-Log Plot (see Figure 8-41)

$H_o = 1.60$ ft

From 4-Cycle Semi-Log Plot at Match Point ($\alpha = 10^{-5}$ Curve) (see Figure 8-42)

$\frac{Tt}{r_c^2} = 1.23 \quad H/H_o = 0.66 \quad t = 180$ sec

$$T = \frac{1.23(0.125)^2}{180} = 1.07 \times 10^{-4} \text{ ft}^2/\text{sec}$$

$$K = \frac{T}{4.00}(30.48) = 8.14 \times 10^{-4} \text{ cm/sec}$$ (using screen length)

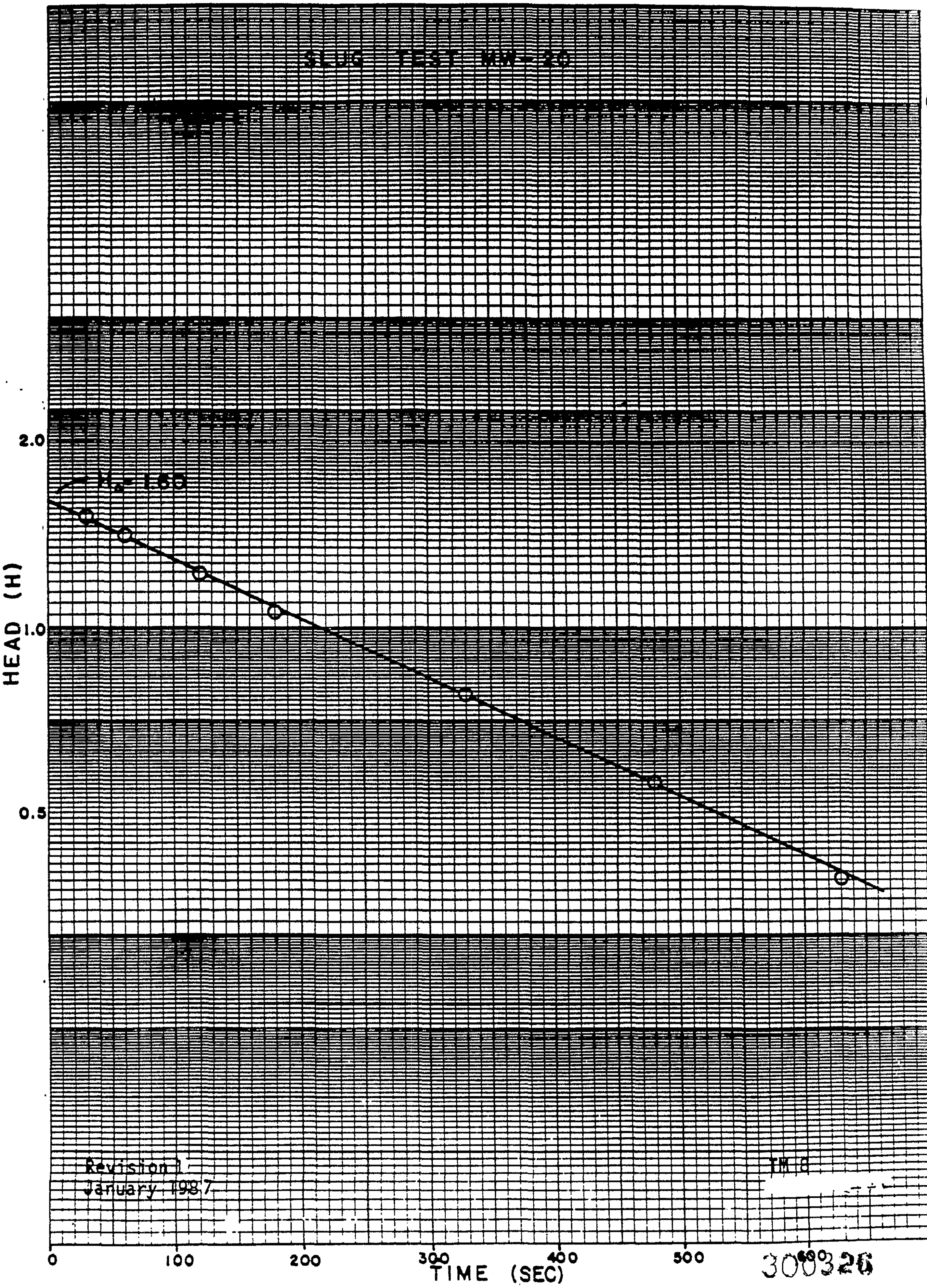
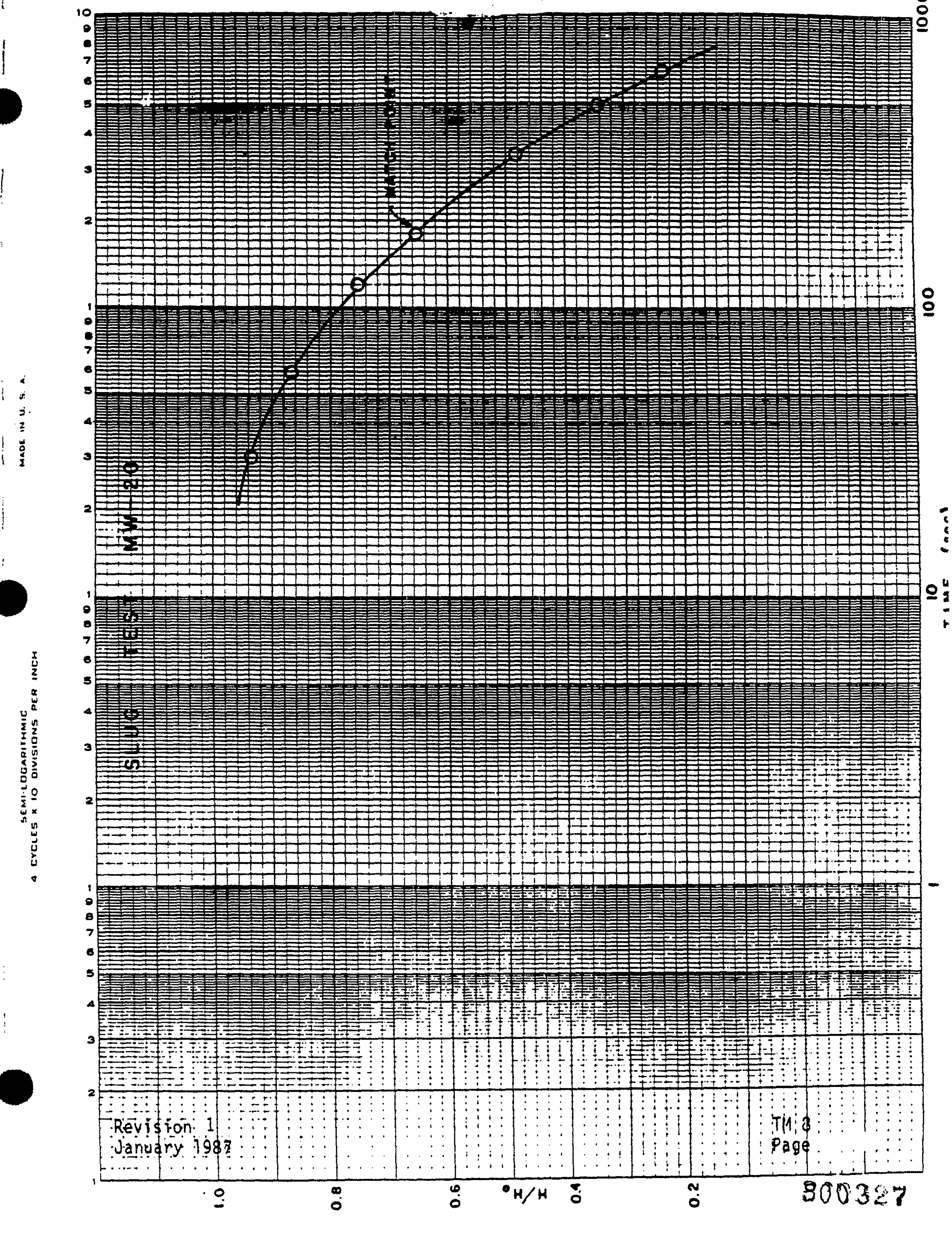


Figure [illegible]-41

SEMI-LOGARITHMIC
4 CYCLES X 10 DIVISIONS PER INCH
MADE IN U. S. A.

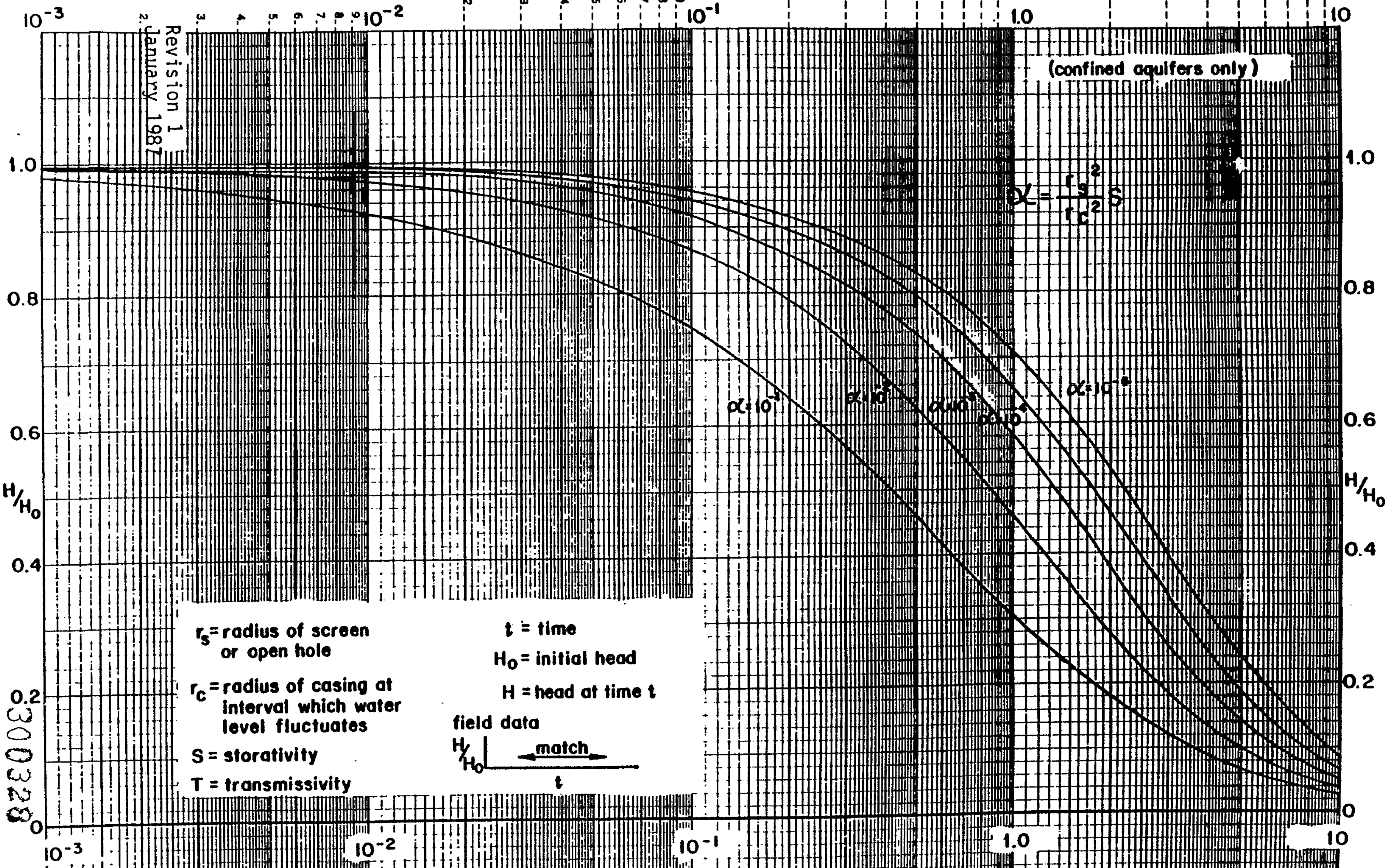
Figure 8-42
Match Point of Data Plot on Type Curve $\alpha = 10^{-5}$



Revision 1
January 1987

TM 3
Page

800327



SLUG TEST TYPE CURVES (after Cooper et al, 1967)

Figure 8-43

The procedure can be applied in stages when a well is being drilled (preferable in unconsolidated materials) or by using packers (in consolidated rocks for vertical isolation of zones).

The following discussion is separated into two sections:

- Procedures for using constant head tests without packers.
- Procedures for using packers in constant head tests.

8.3.1 Constant Head/Constant Flow Tests Without Packers

8.3.1.1 Aquifer Test Design and Field Procedures

Borehole Preparation

1 The borehole should be prepared by one of the following borehole preparation methods, which are listed in order of decreasing accuracy (see Figures 8-28 through 8-33).

F: Standpipe Piezometer (best for low permeability materials below water table) (Figure 8-33).

B or C: Unlined (gravel-filled) test section, cased above (best method above water table if filled only to top of test section) (Figures 8-29 and 8-31).

D: Perforated casing over test section cased above (best method below water table, unless F can be used) (Figure 8-30).

B or C: Unlined (gravel-filled) test section, cased above (if the height of water during the test is maintained above the test section, this method is acceptable only if the casing fits very tightly to the borehole wall) (Figures 8-29 and 8-31).

2. A plastic pipe should be used to introduce water into the well. The pipe is inserted into the test well two to six inches above the base of the hole. This will prevent the entering water from splashing the water level indicator cable, thus precluding withdrawal and drying of the indicator after each reading.

Observation Well preparation

If possible, install one or more observation wells, particularly for tests conducted below the water table. Observation wells can improve the estimate of permeability. Above the water table, observation wells are useful only if the intake and the observation wells penetrate to an impermeable stratum. For tests below the water table, the observation wells should extend at least five feet below the water table.

The observation wells should have as small a diameter as possible to minimize the time required for water to percolate into the well and rise to a height representative of the ground water pressure. This time period has been previously discussed and is referred to as the time lag. However, the observation wells should have an intake of sufficient area that will prevent a clogging problem.

The following borehole preparation methods can be used to prepare the observation wells (see Figures 8-38 through 8-33).

F: Piezometers are used for a low permeability medium. These should not be used in high permeability strata because the permeability of the tip may be less than that of the surrounding mass (Figure 8-33).

A or B: Unlined test section may be cased above (Figures 8-28 and 8-29).

C: Gravel-filled test section is cased above (Figure 8-31).

Test Procedures

1. For the constant head and the constant flow test, select the limiting height of water that will be used in the test.

   In unconsolidated deposits above the water table, the problem of upward seepage around the casing during the test can be eliminated by filling the hole with water only to the top of the test section.

   In weakly cemented rock and cohesive soils, hydraulic fracture may occur if the applied excess head is too great. The applied excess head is defined in this memorandum as the difference between the height H of water in the test well during the test and the heights H_W of water in the well before the test ($H>H_W$). The applied excess head should not exceed 0.5 D/Y_W, where D is the depth to the test section and Y_W is the unit weight of water.

2. Record the temperature of the water that will be added. If possible, bail a small quantity of ground water and measure its temperature. The water added should be slightly warmer than the ground water to prevent bubbles from forming as the added water infiltrates the soil or the rock (USBR, 1951).

At this point, the procedures diverge. For the constant head test, proceed with steps 3, 4, 6, and 7. For constant flow test, proceed with steps 5, 6, and 7.

3. (Constant head test only). If measurements will be at depth, lower the electrical probe into the hole until the electrodes are at the desired depth, (i.e., the height that the water level will be maintained during the test). If two probes are available, lower them so that one is several inches above the other. Secure them in place.

4. (Constant head test only). Begin the flow into the hole. Vary the flow to maintain a constant height of water in the well. If the flow is from a constant head tank, a flow adjustment is not needed. Record the flow rate directly from a flow meter, or by measuring the volume passing the water meter over one minute intervals. In a low permeability medium, it may be possible to shut off the main flow, and measure the flow needed to maintain a constant head by pouring water into the hole and with a calibrated container over a one minute interval.

5. (Constant flow test only). Begin the flow into the hole. Maintain the flow at a constant rate by measuring with a flow meter, water meter, or calibrated container (depending on the rate of flow). Record the depth to the top of the water with an electrical probe, or steel tape or pressure transducer (preferred).

6. (Both tests). Record the flow and the depth to ground water at the following intervals:

    5 minute intervals for 20 minutes
    15 minute intervals for 4 hours
    1 hour for 24 hours

7. Record the data on the data sheet (see Figure 8-44).

Location ______________________

Injection Well No. ______________________

<u>Complete if data recorded for Injection Well:</u>

Depth to top of Test Section in Injection Well ______________

Depth to base of Test Section in Injection Well ______________

I.D. of Injection Well ______________

Perforated Casing (if any) in Injection

Well: % area of slots ______________

Height of Gravel in Injection Well, if any ______________

If Piezometer: Type ______________

Depth to Top/Base of Tip ______________

Depth to Top/Base of Filter ______________

Elevation of Injection Well ______________

Depth to Groundwater ______________

Elevation of Groundwater ______________

Temperature of added water ______________

Temperature of ground water ______________

Name of Operator ______________________

Observation Well No. ______________________

<u>Complete if data recorded for Observation Well:</u>

Depth to top of Observation Section in well ______________

Depth to base of Observation Section in well ______________

I.D. of Observation Well ______________

Perforated Casing (if any) in Observation

Well: % area of slots ______________

Height of Gravel in Injection Well, if any ______________

If Piezometer: Type ______________

Depth to Top/Base of Tip ______________

Depth to Top/Base of Filter ______________

Elevation of Observation Well ______________

Depth to Groundwater ______________

Elevation of Groundwater ______________

t_i	Δt	$t_{ave.}$	V_t	ΔV	Q	D_w	H_t
Time	Time Between Readings	Time at Middle of Time Interval $t_{ave} = \frac{t_{i+1}+t_i}{2}$	Water Meter Reading at Time t	Change in Water Meter Reading over Δt	Flow Over Time Δt $Q = \Delta V/\Delta t$ Q = flow at time $t_{ave.}$	Depth to Water at Time t	Height of Water in Well at Time t

Figure 8-44 CONSTANT HEAD TEST DATA SHEET

300332

8.3.2 Constant Head Test with Packers

A packer test is a type of constant head test and is analyzed in a similar manner. However, the equipment and the procedures required to operate at high pressures are more complex than a constant head test with gravity-induced water pressure. As a result, the methods for conducting packer tests are separately presented.

A possible set-up for packer testing is shown in Figure 8-45.

8.3.2.1 Equipment Selection

1. **Packer Selection** - A packer is an expandable plug. This plug is used at the top, or the top and bottom of a permeability test section to hydraulically isolate the test section from the remainder of the borehole. Packer selection is the key to a successful pressure test. The packer must have sufficient dimensions to ensure that leakage is not a problem. The selected packer should have a length that is at least five times the borehole diameter (USBR, 1951). In erodible formations, a longer unit of several packers in series may be required to obtain a good seal. The packer must be flexible enough to deform to the irregular shape of the borehole.

   Two principal types of packers acceptable for packer testing are mechanical packers and pneumatic packers.

   There are several types of mechanical packers including wedge type, bottom set, and screw set. Wedge type packers are simple but useful only to 25 psi (Acker, 1974). Both bottom set and screw set packers have a rubber cylinder, which is mechanically expanded against the sides of the borehole by compressing the cylinder.

   The bottom set type has the rubber cylinder located between the drill rods attached to the drill. The rubber cylinder is located between the drill rods that extend to the bottom of the borehole and drill rods attached to the drill. The rubber cylinder is compressed and expands laterally when the drill rods are loaded by jacking them against the drilling machine.

   The screw type solid rubber packer uses an adjusting nut to compress the packer. This type of packer is suitable for hard rock and moderately jointed, non-caving, non-erodible formations. Although it can be used to higher pressures than pneumatic packers, the difficulty of applying torque at greater depth limits its utility.

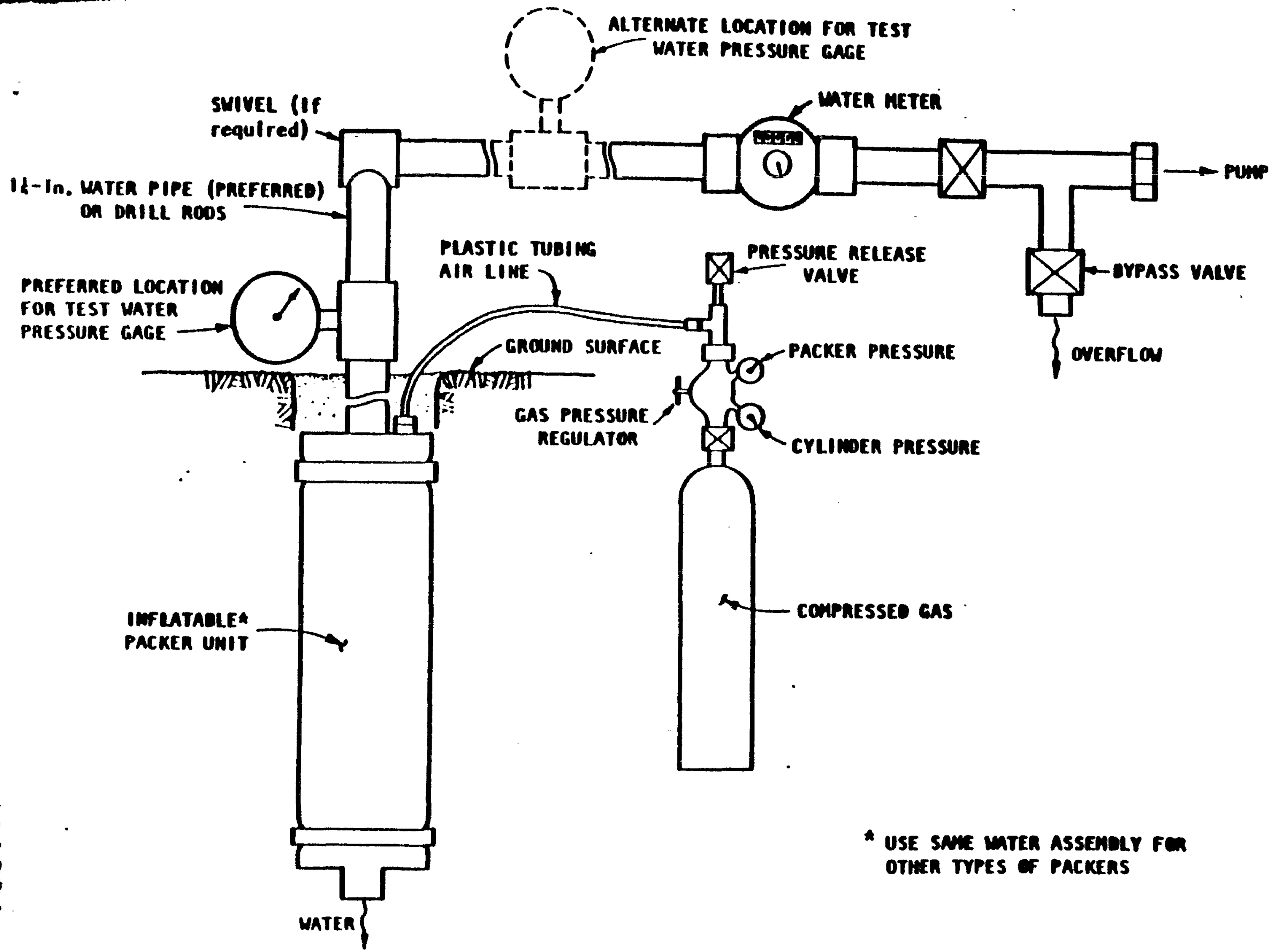


Figure 8-45 PACKER TEST SET-UP (After WCC, 1977)

Pneumatic packers are the most popular type of packer in current practice (Maini, 1971). They are recommended for sedimentary formations, irregular borehole profiles, and caving and erodible material. However, operational pressure criteria may present limitations to the currently practiced pneumatic packer construction.

A basic criterion to in-situ permeability measurement by the packer test method is that the excess test cavity pressure may not exceed 0.5 psi/ft depth to the test section. Otherwise, hydraulic fractures may occur that significantly alter the subsequent test results. Generally, this is not a problem for present test methods and equipment down to depths of approximately 400 feet. The main necessity is to expand the packer at a small differential pressure above the test cavity pressure. A minimum differential of 5 psi is needed. Herndon and Lenahan (1976), and Gale (1975) have found that a differential pressure of 30-40 psi is sufficient to seal the majority of the leaks.

Considering that about 200 psi is the maximum differential pressure reported for the previously constructed pneumatic packers (Sherard et al. 1963), about 165 psi will be the maximum desirable differential injector pressure over any in-situ ground-water pressure in the test zone when making in-situ permeability test measurements. Consequently, for test zones greater than about 380 feet in depth, and when offsetting ground-water pressure is not acting on the test zone, a downhole pressure regulating valve could be installed in the injection pipe above the packer to limit the injection water pressure to 165 psi and thereby avoid leakage past a packer inflated at maximum pressure.

Hydraulic packers have also been reported in field permeability testing. Depending on the suitability of the hydraulic pressure control furnished for the packer operation, these packers can be equally as effective as pneumatically actuated packers. Automatic, continuous hydraulic pressure regulation during testing is equivalent to the gas regulation system and more desirable. Hydraulic packers that utilize shear pins for control of the seating pressure and do not permit pressure adjustment during testing are considered too insensitive for permeability testing requirements.

Packer tests can be performed either in a stage test format, where tests are performed incrementally as the borehole is advanced, or in a continuous series of tests after the entire length of borehole has been advanced. The former technique uses only one packer, because the bottom of the borehole represents the bottom of the test section.

A minimum of two packers are required where the borehole is drilled to its final depth before the testing begins. In the latter case, the packers are connected by a perforated pipe. This pipe spans the test cavity and may be 5 to 20 feet long. It should have a perforated area of at least twice the cross-sectional area of the pipe (USBR, 1951).

In erodible formations, where it is difficult to seal the packer, it may be desirable to use several packers in a series to obtain a good seal. In caving formations where casing is required, the top few inches of the pneumatic packer may be left in the casing to facilitate easy packer withdrawal. However, this practice shortens the length of packer seal below the casing, and may allow leakage past the packer (USBR, 1951).

2. **Size of Rod or Pipe** - Drill rods are not recommended for use in packer testing. Friction losses become excessive when the flow through the rods exceeds 15 gpm or when the length of the rods is more than 50 feet. A 1-1/4 inch pipe is more satisfactory for moderate depths.

   A graph that displays pressure losses per 10-ft section at various delivery rates of water, for several drill rod sizes and 1-1/4 inch pipe is provided in Figure 8-46. The curves, plotted by the USBR (1951), were compiled from tests where the pressure gauge was set between the swivel and the pump. Therefore, the swivel ffriction losses are included.

   The 1 and 1-1/2 inch swivels were used in the tests, with nominal diameters of 1/2 and 3/4 inch, respectively. It can be observed that at high rates (>100 gpm), even the 1-1/4 inch diameter pipe will effect significant head losses.

   When testing at large depths in a highly permeable strata, large flow rates may be required to produce the desired pressures. In such cases, a larger diameter pipe is required to reduce the friction losses.

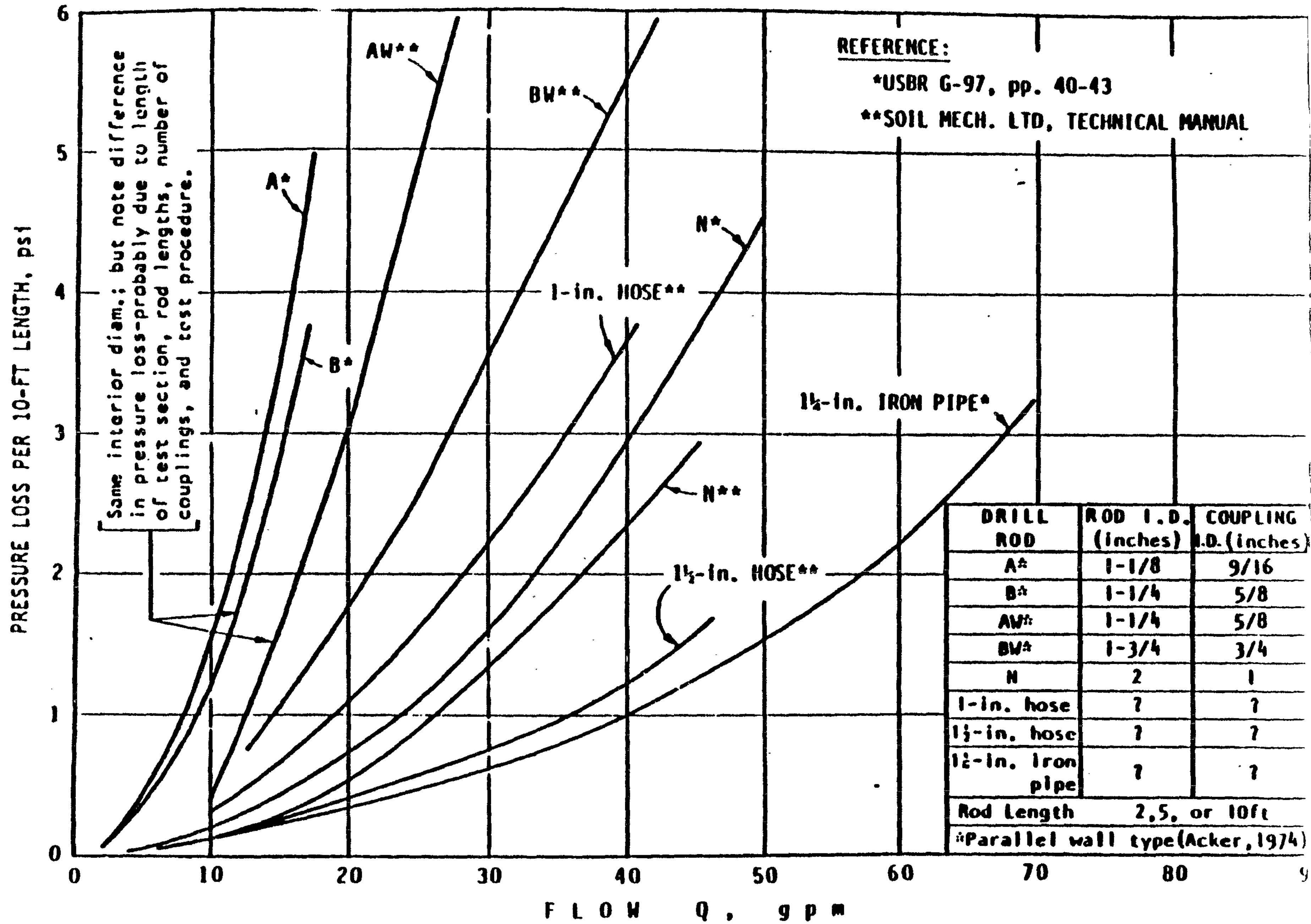


Figure 8-46 CALIBRATING PRESSURE LOSSES IN DRILL RODS/WATER PIPE
(After WCC, 1977)

300337

3. **Pumping Equipment** - In past practice, many packer tests have been run by using the circulation pump on the drill for pumping the water. Such pumps are often the multiple cylinder type, which delivers a fluctuating pressure. These pumps are not recommended, because the fluctuating pressures are often difficult to accurately read, and averaging is required to estimate the true pressure.

   Instead, a centrifugal pump should be used. The required capacity of the pump will vary with the depth of the test section and the permeability of the rock/soil mass. However, a 350 gpm pump capacity against a dynamic head of 300 feet (excess head in test cavity) should be adequate for most tests.

   Higher capacity pumps may be required to overcome friction losses in the pipe. Drill rigs used for performing pressure tests should be equipped with auxiliary pumps of this type (USBR, 1951).

4. **Swivels** - Swivels used on the majority of the drill rigs have a narrow constriction that carries a considerable loss of pressure as the water passes through. Swivels with a uniform inside diameter are recommended for packer testing.

5. **Location of Pressure Gauge** - In most tests, the pressure gauge is located between the pump and the water meter or between the water meter and the swivel. Although the latter location is less objectionable, the necessity for estimating pressure loss in the water swivel can be avoided if the pressure gauge is located near the top of the pipe or rod used for testing, which is between the packer and the swivel. In this case, the fitting for the gauge should be located below the bottom of the swivel at a distance of at least 10 times the diameter of the pipe or the rod (USBR, 1951).

6. **Recommended Types of Water Meters** - Required water deliveries in packer tests may range from less than 1 gpm up to 400 gpm. There is not a sufficiently accurate meter that can be used for all ranges of flow.

   Therefore, the following two meters are recommended for each rig: A 4-inch impeller-type meter will measure the flows greater than 50 gpm. A 1-inch disk-type meter will measure flows between 1 and 50 gpm. When possible, water meters should be tested at least once a month.

Adapters should be available for each water meter. The adapters should be at least 10 times as long as the diameter of the rated side of the meter. This length of the adapter permits the water flow to become steady and eliminates the turbulence due to a change in the pipe diameter. The accuracy of the majority of meters is adversely influenced by turbulent flow. An adapter should be used on the upstream side of each meter when the water from the pump to the meter has a different diameter than the nominal size of the meter (USBR, G-97).

8.3.2.2 Hole Preparation

There are two ways to drill a borehole for packer testing. One drilling procedure is to drill to the desired test depth, case (if required) to the top of the test section, insert the packer, and perform the test. The packer is then removed, and the borehole is drilled to the next test depth.

A simpler procedure is possible in sound rock when casing is not required. The hole may be completely drilled before testing. In this case, the testing begins at the bottom of the borehole and proceeds upwards.

The borehole may be prepared by one of the following preparation procedures (see Figures 8-28 and 8-31).

A: Unlined Borehole (consolidated deposits) (Figure 8-28).

C: Unlined Test Selection, Cased Above (unconsolidated deposits) (Figure 8-31).

If the borehole is unlined (Method A), and is drilled to its final depth before testing begins, it is only necessary to clean the hole once over its full length. If a stage test is conducted in a borehole, the hole must be cleaned prior to each test.

Select a hole diameter between AX and NX (up to 3-inch diameter) (Mulligan, 1975; Sherard, 1963). The smaller the hole diameter, the less the total uplifting force on the packer. For a packer of fixed length, although the total force displacing the packer increases with r^2, the shear resistance along the sides of the packer increases only as r. However, if the down-the-hole-inspection methods are used in conjunction with the permeability test program, a borehole of sufficient diameter to accept the instrument will be required.

The test section should be roughly 10 feet long (USBR, 1951), but may vary from 5 to 20 feet. The hole length can be varied in order to obtain good packer seating or to isolate a specific zone. In very permeable formations, the shorter test length may be needed to build up a back-pressure (USBR, 1951).

8.3.2.3 <u>Test Procedure</u>

1. Prepare the borehole as per the "Hole Preparation" section.

2. Position the packer or packers so that a test section of approximately 10 feet is obtained. If two packers are used to isolate the test section, begin testing at the bottom of the hole. The seating of packers to define the test section length can be adjusted according to the geologic information obtained from core samples and/or down-the-hole surveys, or it can be adjusted according to a pre-specified interval.

3. Prior to expanding the packer(s), record the pretest water pressure (if below the water table) in the test cavity. The difference between this pressure and the cavity pressure measured during testing is the excess pressure applied to the immediate ground mass. This is the pressure that is plotted vs. the observed flow rate into the test section.

4. Investigate possible packer leakage. This can be accomplished with a continuous reading instrument (chart recorder) that monitors the pressure in the test cavity. This procedure can be applied to the stage test (single packer) method or the double packer method, as follows.

   Commence inflow into the system and then incrementally increase the packer pressure. This will contribute to the removal of any large air pockets within the test cavity. As the packer pressure increases, leakage past the packers will decrease, the pressure in the test cavity will increase, and the flow rate into the test cavity (measured by the water meter at the top of the borehole) will consequently decrease.

   After a certain point, further increase of packer pressure will only effect a temporary slight increase in cavity pressure data the instant the packer pressure is increased. This is a dynamic effect, and the cavity pressure will quickly return to a steady state value.

Three graphs that illustrate typical relationship between packer pressure, test cavity pressure, and test cavity inflow throughout the packer sealing procedure are contained in Figure 8-47.

Use caution to ensure that the excess test cavity pressure does not exceed 0.5 psi/ft depth to the test section during this procedure. Otherwise, hydraulic fractures may occur and significantly alter the subsequent test results as discussed earlier.

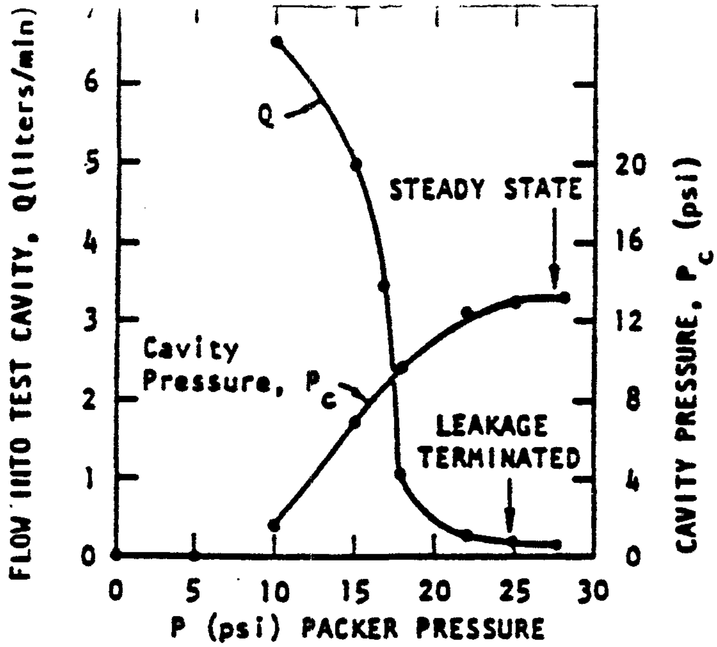
1. Pump water into the test section at a specified constant pressure for 15 to 20 minutes, and take readings of total water flow and pressure at 5-minute intervals (USBR, 1951). The test at this pressure is completed when the flow over two successive 5-minute intervals differs by less than 10 percent.

   In very permeable materials, a test duration of 5 or 10 minutes may be sufficient. In this case, record flow and pressure over 1-minute intervals until stable conditions are reached. Perform this procedure at various applied water pressures. The maximum excess pressure applied should be 0.5 psi/ft depth to the test section.

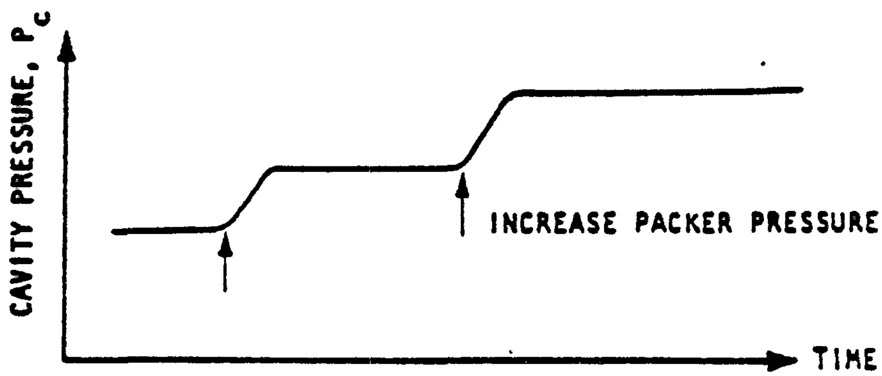
   As an example, consider a test section depth of 100 feet, where the existing water table is 50 feet below the ground level. The pretest pressure in the test section is approximately 22 psi (62.4 lb/ft^3 x 50 ft divided by 144 in^2/ft^2). The maximum allowable excess pressure is 50 psi (0.5 psi/ft x 100 ft). Therefore, during the test, the maximum observable pressure is 72 psi (22 psi existing hydrostatic pressure plus the maximum allowable excess pressure of 50 psi). The value of 72 psi is called P_{max}, and a recommended pressure sequence is 1/2 P_{max}, 3/4 P_{max}, P_{max}, 3/4 P_{max}, and 1/2 P_{max}.

6. Record the data on a form similar to that in Figure 8-48, where the Test Section Pressure P_T is directly measured by the transducer. The data can be analyzed to compute the permeability, as discussed in Section 8.3.3.

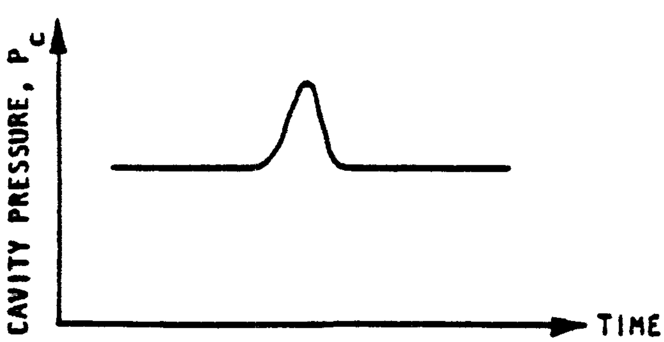
7. Plot the data as pressure (vertical scale) vs. flow. Compare the data with Figure 8-49 for evidence of problems such as: leakage around packer, erosion of test zone, and clogging fissures. A high quality test should provide a linear plot similar to that corresponding to laminar flow in Figure 8-49.



(a) TYPICAL DATA INDICATING SEALING OF PACKER



(b) CHART RECORD OF TEST CAVITY PRESSURE WHILE INCREASING PRESSURE IN A LEAKY PACKER (Increases in Packer Pressure divert additional leakage into test cavity, thereby raising cavity pressure, P_c)



(c) CHART RECORD OF TEST CAVITY PRESSURE WHILE INCREASING PRESSURE IN A NON-LEAKING PACKER (Transient Peak in Cavity Pressure, P_c, due to increase in packer pressure indicates effective packer seal)

Figure 8-47 MONITORING PACKER LEAKAGE IN PACKER TESTS

(Maini, 1971)

8. For the stage-test procedure, remove the packer, and prepare the borehole for the next test. In a predrilled hole, where two packers are used to isolate the test section, the packers are simply raised to the next test depth.

8.3.3 Constant Head, Constant Flow, and Packer Tests Analytical Procedures

These analytical methods may be applied to any pump-in test where a steady state condition is achieved (i.e., both Q, the in-flow, and H, the height of water in the injection well become constant over time). Therefore, they can be used for constant head tests, packer tests, and constant flow tests.

Several analytical methods are available in the literature. Research by Schmid (1967) has shown that there is a good agreement among the range of formulas. For example, the variation in value of K computed may vary by a factor of 2 between the methods of analysis developed by Schmid and Hvorslev. This variation is within the standard deviation of field test results, even from similar, carefully performed field tests that use a single analytical method.

For saturated media, Hvorslev (1951) developed the basic analysis of constant head tests. His assumptions are the same as those provided for variable head test analyses in Section 8.2.3.2. The USBR (Earth Manual) analysis method, which is applicable for packer tests, is considered more accurate for tests below the ground-water table than above the ground-water table.

When one or more observation wells are available, Schmid (1967) has developed a solution that provides the permeability over a larger area and is less influenced by local variations in the soil/rock medium. If observation well data are available, the data should be used in the permeability calculation. The Hvorslev's, the USBR (Earth Manual), and the Schmid's analysis methods are presented.

Selected analytical methods are presented for unsaturated media (2); for a zone above the water table saturated by capillary action (1), and for unsaturated materials overlying on impermeable bed (USBR, G-97) (1).

8.3.3.1 Selected Analytical Methods and Examples

Determine the following steady state conditions:

Location ______________________

Borehole No. ______________________

Depth of Bottom of Borehole ______________________

Depth of Top of Test Section ______________________

Depth of Base of Test Section ______________________

Depth of Casing ______________________

Diameter of Borehole ______________________

Type of Drill Rod/Water Pipe ______________________

I.D. of Drill Rod/Water Pipe ______________________

Length of Drill Rod ______________________

Packer Type ______________________

Packer Length (Upper) ______________________

Name ______________________

Date ______________________

Elevation ______________________

Depth to Ground Water ______________________

Elevation of Ground Water ______________________

Height of Pressure Gage above Ground Level ______________________

Length of Hose between pressure gage and drill rod ______________________

Nominal I.D. of hose ______________________

Swivel type ______________________

Nominal I.D. of swivel ______________________

<u>If two Packers Used:</u>

Packer Length (Lower) ______________________

Length of Test Section ______________________

Water pipe I.D. ______________________

Area of pipe perforations ______________________

SYMBOL:	P_P	P_L	H_E	P_E	P_T	t	V_W	Δt	ΔV_W	Q	H_T
ITEM:	Water Gage Pressure	Pressure Loss in Drill Rods and Hose*	Static Head Gain: Elev. of Press. Gage - Elev. of Middle of Test Section	Pressure Gain due to H_E = $H_E \cdot \gamma_W$ Where γ_W = unit Weight of Water	Test Section Pressure $= P_E + P_P - P_L$	Time (min) From Start of Test	Water Meter Reading at Time t	Time (min) Between Readings	Change in Water Meter Reading Between Readings	Flow = $\Delta V_W/\Delta t$	Head at Test Section $= P_T/\gamma_W$ γ_W = unit Weight of Water
UNITS:						min		min			

*If calibration test run, see Figure 7-7. Otherwise, see Figure 7-5.

Figure 8-48 PACKER TEST DATA SHEET

300344

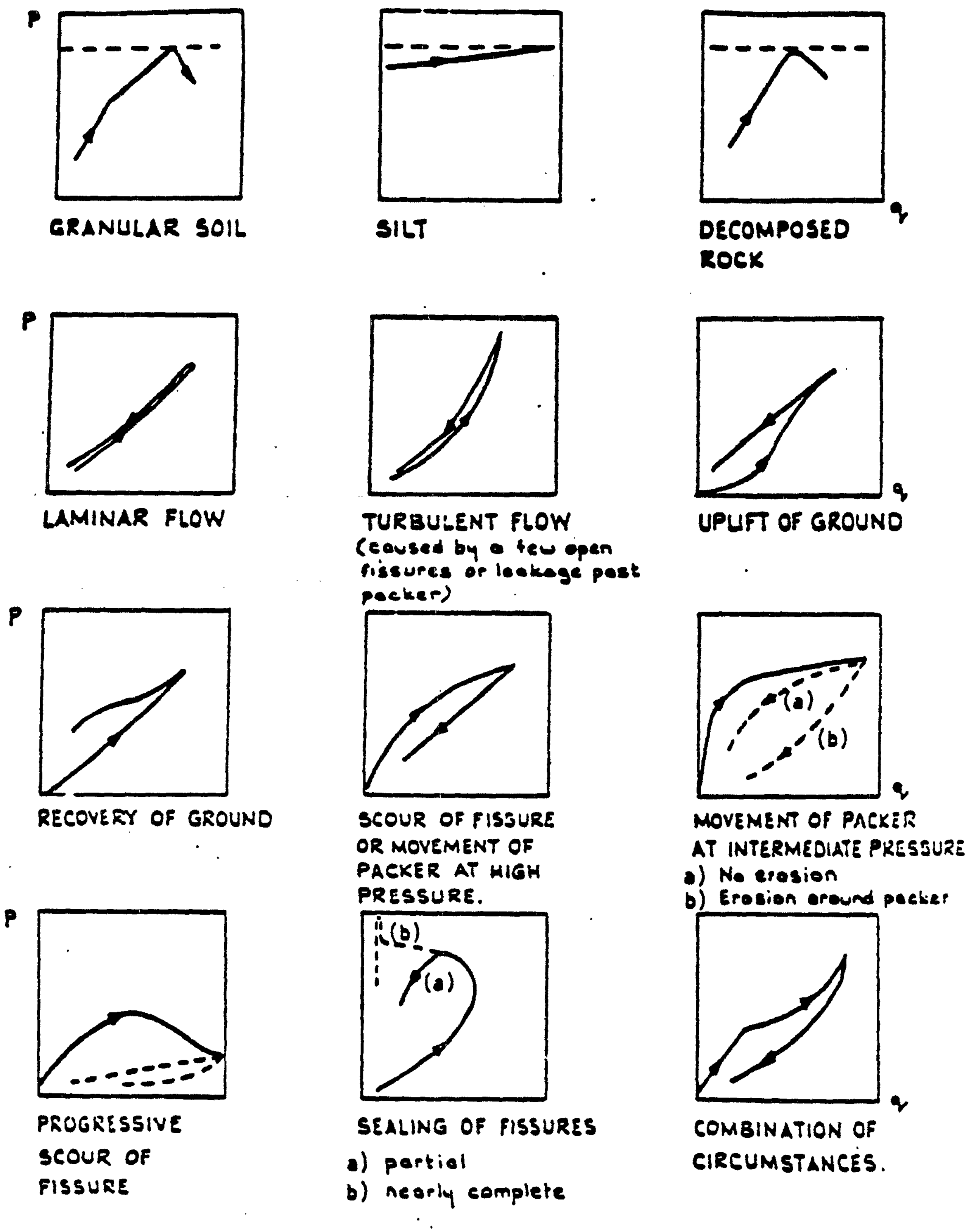


Figure 8-49 TYPICAL PRESSURE VERSUS FLOW CURVES FOR PACKER TESTS

(Dixon, 1975)

Let H = height of water in well above base of test zone
Q = flow rate of water
t = time

For constant flow tests, plot H versus log t. (Note: if a transducer is used to measure the head in psi, use conversion 1 psi = 2.31 ft of water.) Find H as $t \rightarrow 0$. This is the steady state head in the well.

For constant head tests, plot Q versus log 1/t. Find Q as $1/t \rightarrow 0$. This is the steady state flow. For packer tests, prepare one plot for each applied pressure.

Determine the effective head at test zone (Packer Test only).

If the pressure is measured with a pressure gauge above the ground surface, estimate the head loss, H_L, in the drill rods and hose between the pressure gauge and the test station. These must be provided by calibrating the equipment before the test. The head loss $H_L = P_L$ (Yw), where P_L is measured pressure loss in the system and Y is the unit weight of water. If calibration curves have not been developed for the specific test equipment, the head loss H_L can be estimated by using Figure 8-46.

H_p is the pressure head added by the pump and measured at the pressure gauge.

H_{elev} is the height of the column of water from the bottom of the test section to the pressure gauge.

Then $H = H_p - H_{elev} - H_L$ = the effective head at the test zone.

Note: If a pore pressure transducer is used, the effective head at the test zone is directly obtained by measuring the pressure in the test cavity, and converting it to the equivalent head of water.

Determine the "Zone" of the test (see Figure 8-50).

The zones defined below are developed in the USBR publication G-97.

Zone 1: Above the water table and unsaturated.

Zone 2: Above the water table, but saturated by capillary action or close enough to the water table to create a continuous saturated zone between the test section and the water table during the test.

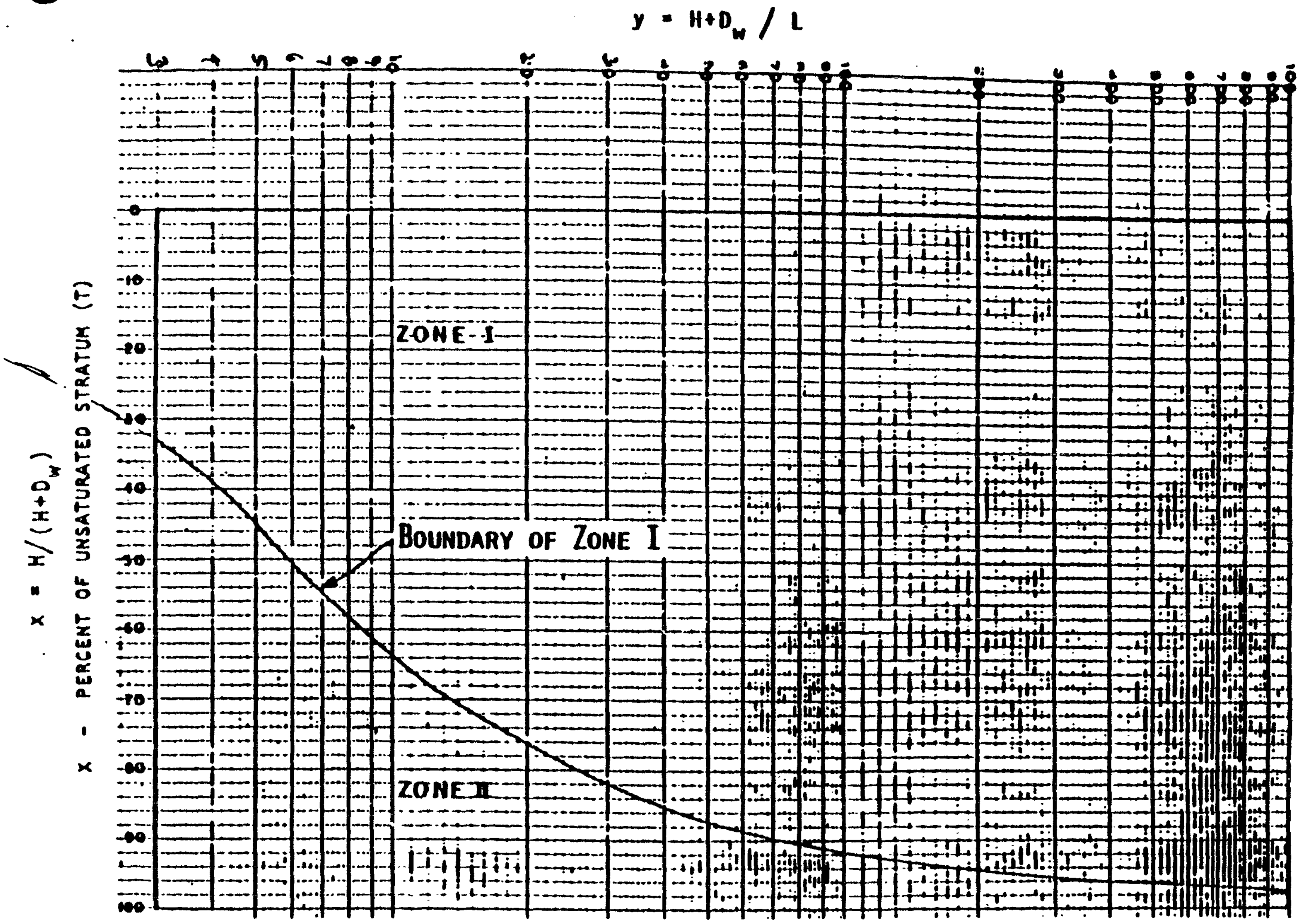


Figure 8-50 LOCATION OF ZONE I / ZONE II BOUNDARY
(USBR, G-97)

300347

Zone 3: Below the water table.

D_W: The depth from the base of the test section to the ground water level or to an impermeable stratum. For purposes of creating a partially saturated zone in the vicinity of the test section, an impermeable stratum is equivalent to the water table (USBR, Earth Manual) (Zones 1 and 2)

L: Length of the test section.

H_W: The pretest ground water level in the well.

To determine whether the test is in Zone 1 or 2, calculate the following equations:

$$Y = \frac{H + D_W}{L}$$

$$X = \frac{H}{H + D_W}$$

To determine the "Zone", enter Figure with X and Y.

Estimate the constant head H_C for calculations.

Zone 1: $H_c = H$

Zone 2: $$H_C = \frac{(H + D_W) + (H - L)}{2}$$

Zone 3: $H_c = H_W$

To complete the shape factor F for a specific test well geometry and test zone in constant head tests, use data only from the test well. Refer to Figures 8-51 through 8-53 for the USBR G-97 method, to Figure 8-54 for the USBR Earth Manual method (packer test only), or to Figure 8-55 for the Hvorslev method. An example of the calculation procedure for the Earth Manual Method E-18 is located in Figures 8-56 through 8-58.

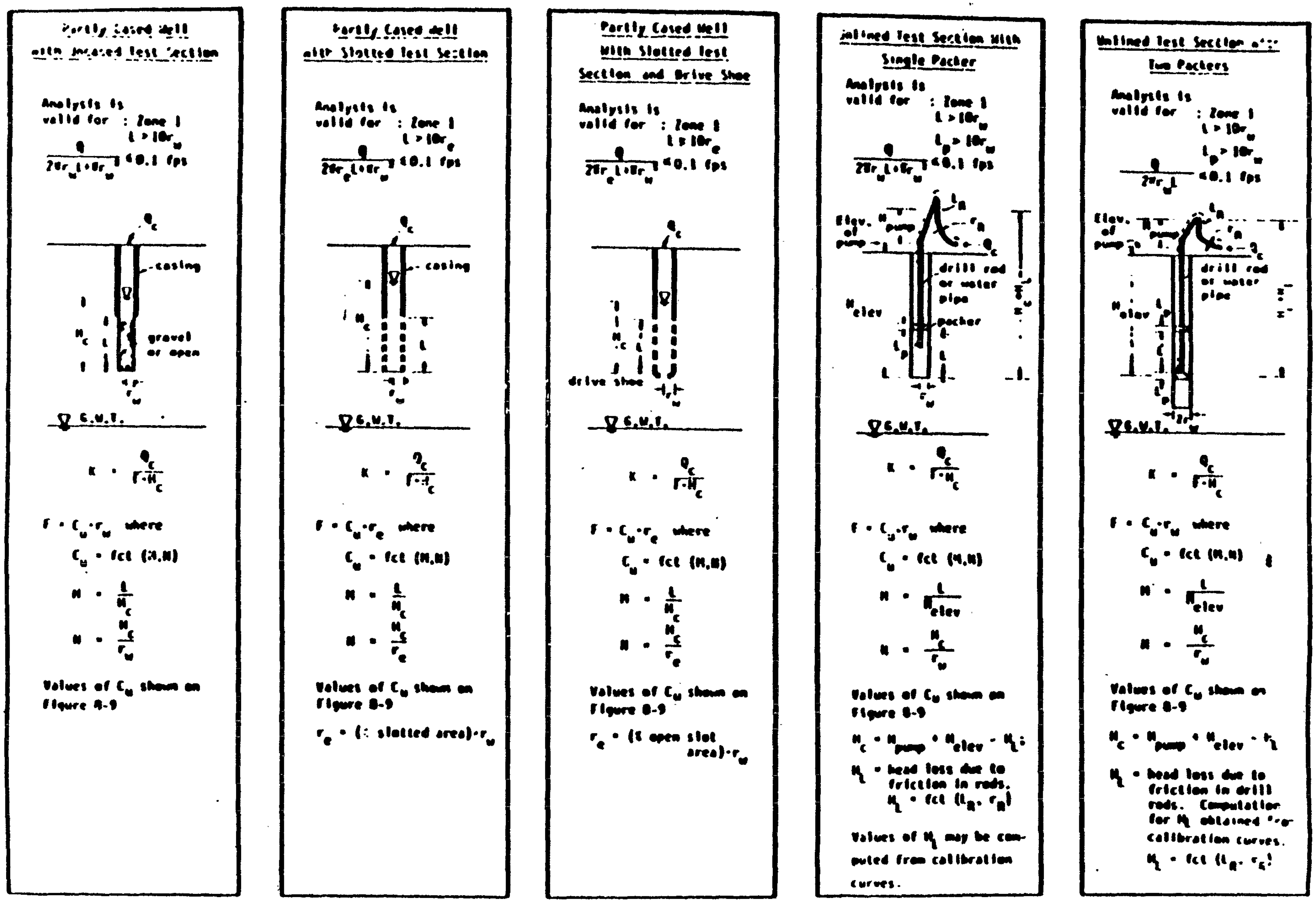


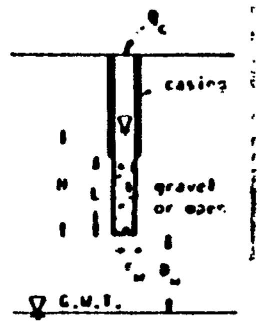
Figure 8-51 USBR ANALYSIS METHOD FOR CONSTANT HEAD TEST - ZONE I (ABOVE WATER TABLE, UNSATURATED) (after USBR, 6-9?)

Partly Cased Well With Uncased Test Section

Analysis is valid for : Zone 2

$L > 10r_w$

$\frac{Q}{2\pi r_w(L+8r_w)} \le 0.1$ fps



$$K = \frac{Q_c}{F \cdot H_c}$$

$$H_c = \frac{(H + D_w) + (H - L)}{2}$$

$F = (C_s + 4) \cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

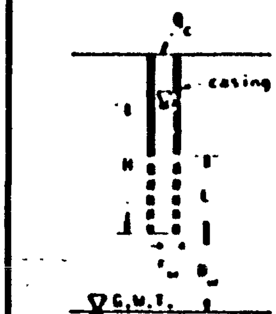
$$C_s = 5.30\left(\frac{L}{r_w}\right)^{0.73}$$

Partly Cased Well With Slotted Test Section

Analysis is valid for : Zone 2

$L > 10r_e$

$\frac{Q}{2\pi r_e(L+8r_w)} \le 0.1$ fps



$$K = \frac{Q_c}{F \cdot H_c}$$

$$H_c = \frac{(H + D_w) + (H - L)}{2}$$

$F = C_s r_e + 4r_w$

r_e = (% open slotted area) $\cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

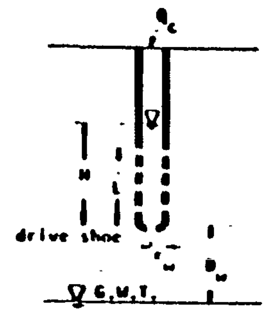
$$C_s = 5.30\left(\frac{L}{r_e}\right)^{0.73}$$

Partly Cased Well With Slotted Test Section and Drive Shoe

Analysis is valid for : Zone 2

$L \geq 10r_e$

$\frac{Q}{2\pi r_e(L+8r_w)} \le 0.1$ fps



$$K = \frac{Q_c}{F \cdot H_c}$$

$$H_c = \frac{(H + D_w) + (H - L)}{2}$$

$F = C_s r_e + 4r_w$

where r_e = (% open slotted area) $\cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

$$C_s = 5.30\left(\frac{L}{r_e}\right)^{0.73}$$

(Omit the term $4r_w$ if a clay seal placed at bottom of casing)

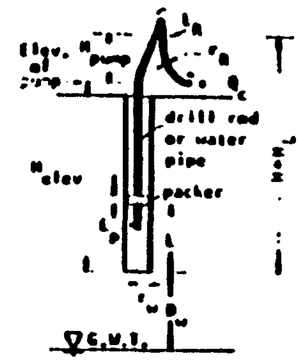
Unlined Test Section With Single Packer

Analysis is valid for : Zone 2

$L > 10r_w$

$L_p > 10r_w$

$\frac{Q}{2\pi r_w(L+8r_w)} \le 0.1$ fps



$$K = \frac{Q_c}{F \cdot H_c}$$

$$H_c = \frac{(H + D_w) + (H - L)}{2}$$

$H = H_{pump} + H_{elev} - H_L$

where H_L = friction loss in drill rods = fct (L_R, r_R)

H_L can be computed from calibration curves.

$F = (C_s + 4) \cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

$$C_s = 5.30\left(\frac{L}{r_w}\right)^{0.73}$$

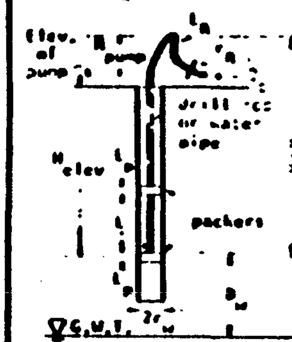
Unlined Test Section with Two Packers

Analysis is valid for : Zone 2

$L > 10r_w$

$L_p > 10r_w$

$\frac{Q}{2\pi r_w L} \le 0.1$ fps



$$K = \frac{Q_c}{F \cdot H_c}$$

$$H_c = \frac{(H + D_w) + (H - L)}{2}$$

$H = H_{pump} + H_{elev} - H_L$

where H_L = friction loss in drill rods = fct (L_R, r_R)

H_L can be computed from calibration curves.

$F = C_s \cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

$$C_s = 5.30\left(\frac{L}{r_w}\right)^{0.73}$$

Figure 8-52 USBR ANALYSIS METHOD FOR CONSTANT HEAD TEST - ZONE 2 (ABOVE WATER TABLE, SATURATED BY CAPILLARY ACTION)
(after USBR, 6-97)

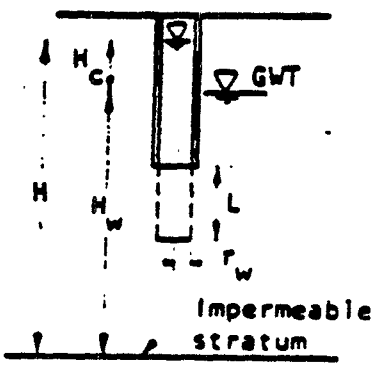
Partly Cased Well With Slotted Test Section

Analysis is valid for : Zone 3

$L > 10r_e$

$$\frac{Q}{2\pi L r_e + \pi r_w^2} \leq 0.1 \text{ fps}$$

$H_w > 5L$



$$K = \frac{Q_c}{F \cdot H_c}$$

$H_c = H - H_w$

$F = C_s \cdot r_e + 4r_w$

where

r_e = (open slotted area)$\cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

$$C_s = 5.30\left(\frac{L}{r_e}\right)^{0.73}$$

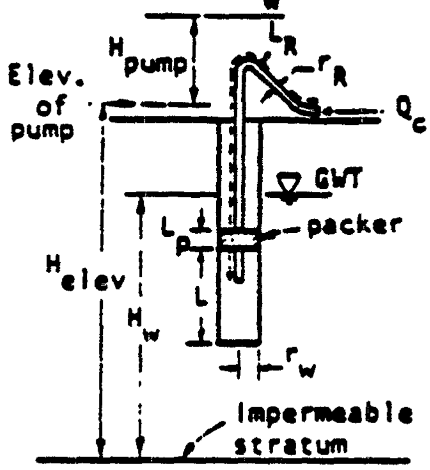
Unlined Test Section With Single Packer

Analysis is valid for : Zone 3

$L \geq 10r_w$

$$\frac{Q}{2\pi L r_w + \pi r_w^2} \leq 0.1 \text{ fps}$$

$H_w \geq 5L$



$$K = \frac{Q_c}{F \cdot H_c}$$

$H_c = H - H_w$

$H = H_{elev} + H_{pump} - H_L$

where H_L = head loss due to friction in drill rods.

H_L = fct (L_R, r_R) and H_L may be computed based on calibration curves

$F = (C_s + 4) \cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

$$C_s = 5.30\left(\frac{L}{r_w}\right)^{0.73}$$

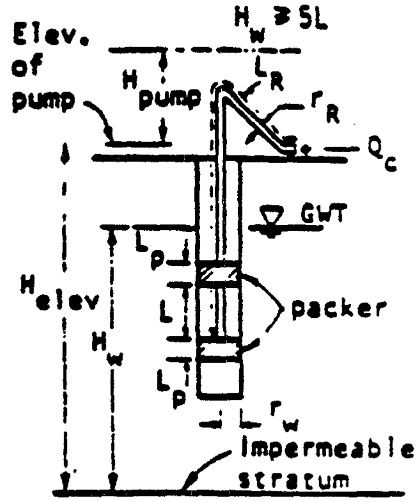
Unlined Test Section With Two Packers

Analysis is valid for : Zone 3

$L \geq 10r_w$

$$\frac{Q}{2\pi L r_w} \leq 0.1 \text{ fps}$$

$H_w \geq 5L$



$$K = \frac{Q_c}{F \cdot H_c}$$

$H_c = H - H_w$

$H = H_{elev} + H_{pump} - H_L$

where H_L = head loss due to friction in drill rods.

H_L = fct (L_R, r_R) and H_L may be computed based on calibration curves

$F = C_s \cdot r_w$

Values of C_s are given in Figure 8-8, or can be approximated from:

$$C_s = 5.30\left(\frac{L}{r_w}\right)^{0.73}$$

Figure 8-53 USBR ANALYSIS METHOD FOR CONSTANT HEAD TEST - ZONE 3 (BELOW WATER TABLE)
(after USBR, G-97)

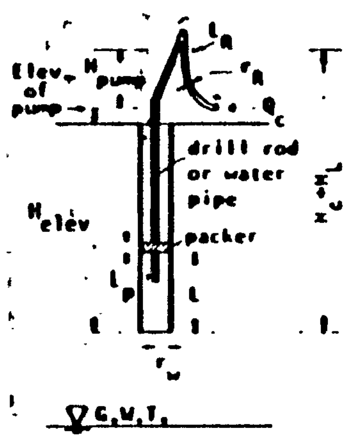
• ABOVE THE WATER TABLE •

Unlined Test Section With Single Packer

Analysis is valid for :

$L > 10r_w$

$L_p > 10r_w$



$$K = \frac{Q_c}{F \cdot H_c}$$

$H_c = H_{pump} + H_{elev} - H_L$;

H_L = head loss due to friction in rods. $H_L = fct\ (L_p, r_p)$

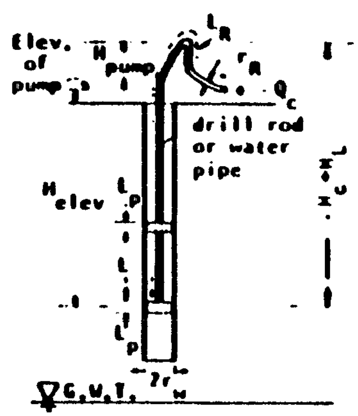
Values of H_L may be computed from calibration curves.

Unlined Test Section With Two Packers

Analysis is valid for :

$L > 10r_w$

$L_p > 10r_w$



$$K = \frac{Q_c}{F \cdot H_c}$$

$H_c = H_{pump} + H_{elev} - H_L$

H_L = head loss due to friction in drill rods. Computation for H_L obtained from calibration curves.

$H_L = fct\ (L_R, r_R)$

• BELOW THE WATER TABLE •

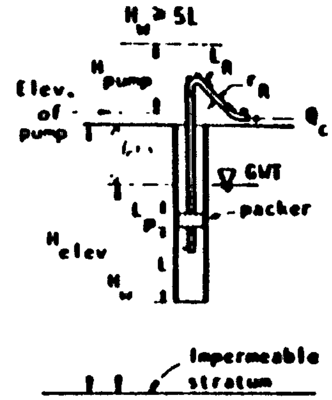
Unlined Test Section With Single Packer

Analysis is valid for :

$L \geq 10r_w$

$L_p > 10r_w$

$H_w \geq 5L$



$$K = \frac{Q_c}{F \cdot H_c}$$

$H_c = H - H_w$

$H = H_{elev} + H_{pump} - H_L$

where H_L = head loss due to friction in drill rods.

$H_L = fct\ (L_R, r_R)$ and H_L ray be computed based on calibration curves

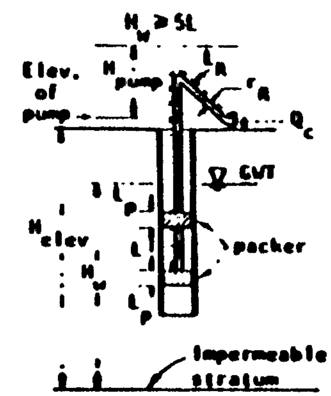
Unlined Test Section With Two Packers

Analysis is valid for :

$L \geq 10r_w$

$L_p > 10r_w$

$H_w \geq 5L$



$$K = \frac{Q_c}{F \cdot H_c}$$

$H_c = H - H_w$

$H = H_{elev} + H_{pump} - H_L$

where H_L = head loss due to friction in drill rods.

$H_L = fct\ (L_R, r_R)$ anc H_L may be computed base: on calibration curves

For all cases: $F = \dfrac{2\pi L}{\ln(L/r_w)}$

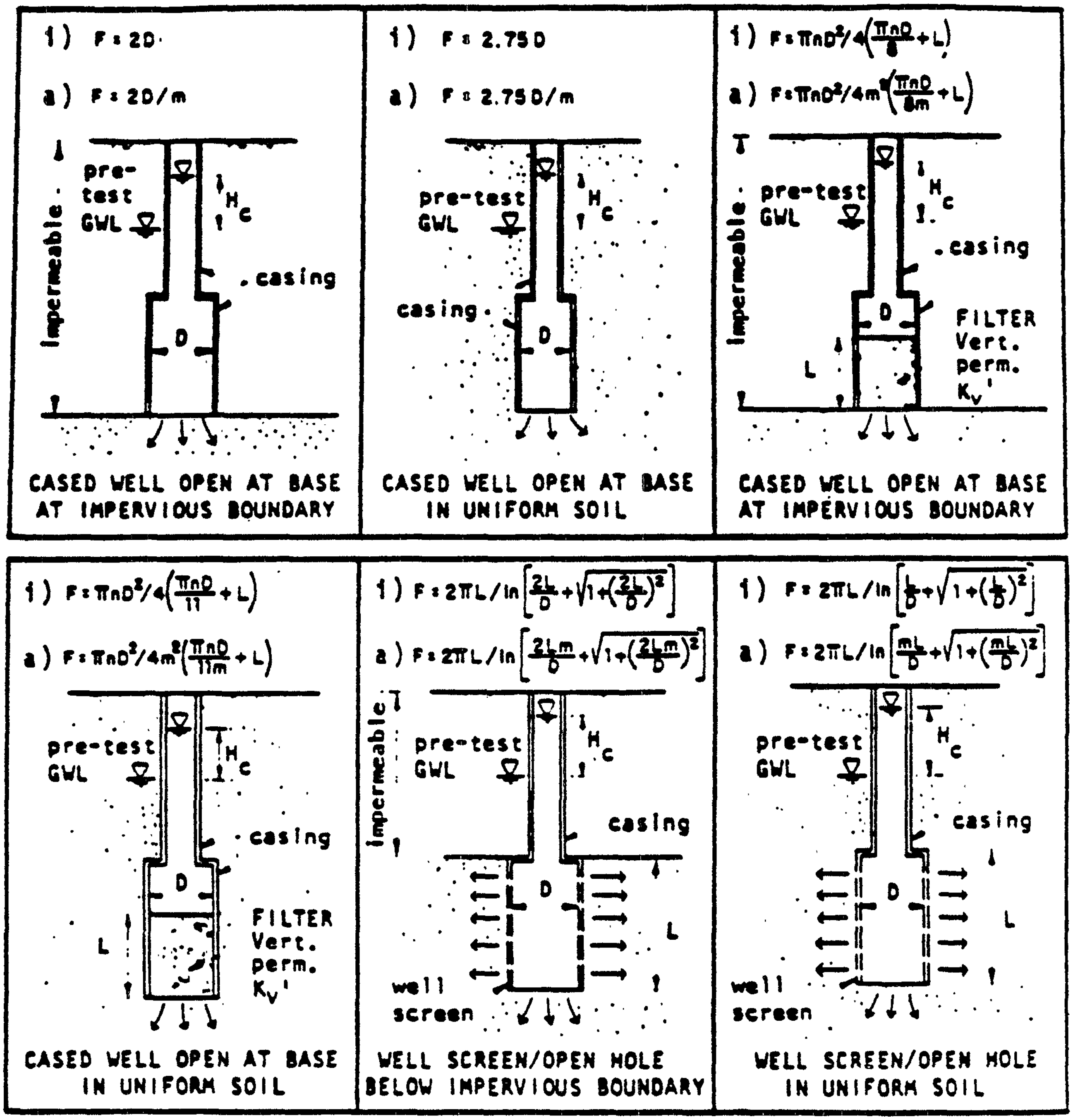
Figure 8-54 USBR (EARTH MANUAL) ANALYSIS METHOD FOR CONSTANT HEAD TEST
(after USBR Earth Manual, 1974)

300352

i isotropic conditions: $K_h = K_v = K$

a - anisotropic conditions: $K_h \neq K_v$

$$K \text{ or } K_h = \frac{Q_c}{(F \cdot H_c)}$$



<u>DEFINITIONS:</u> $K_m = \sqrt{K_v K_h}$; $m = \sqrt{K_h/K_v}$; $n = K_v'/K_v$

where K_v = vertical permeability of soil/rock mass

K_h = horizontal permeability of soil/rock mass

K_v' = vertical permeability of filter in casing

Figure 8-55 HVORSLEV'S ANALYSIS METHOD FOR CONSTANT HEAD TEST - ZONE 3 (BELOW WATER TABLE) (1951)

FIGURE 8-56

PACKER TEST DATA SHEET

Project 42174A
Borehole No. BH-1
Depth of Bottom of Borehole 39.6'
Depth of Top of Test Secction 33.3'
Depth of Base of Test Section 39.6'
Diameter of Borehole NQ = 3"
Type of Drill Rod/Water Pipe galvanized
I.D. of Drill Rod/Water Pipe 1"
Length of Drill Rod 30 feet (pipe)
Packer Type pneumatic
Packer Length (lower) none
Packer Length (upper) 2.0'
Length of Test Section 6.3'

Name Scholl Canyon Barrier
Date 7-3-86
Elevation
Depth to Ground Water approx. 41'
Elevation of Ground Water
Height of pressure gage above ground level 0.0'
Length of hose between pressure gauge and drill rod ~ 15 ft.
Nominal I.D. of hose 1"
Swivel type none
Nominal I.D. of Swivel —
Water pipe I.D. —
Area of pipe perforations —

P_T test section pressure (psi)	t time from start of test (min)	V_W water meter reading at time t (gal)	Δt time between reading (min)	ΔV_W change in water meter reading between readings (gal)	Q Flow = $\Delta V_W/\Delta t$ (gpm)	H_T Head at test section = P_T/γ_W water (ft)
8	0'00"	8.50	0'00"	—	—	
	5'00"	7.85	5'00"	0.65	0.13	
	10'00"	7.60	5'00"	0.15	0.03	
	15'00"	7.55	5'00"	0.05	0.01	
	20'00"	7.55	5'00"	0.00	0.00	
11	0'00"	7.55	0'00"	—	—	
	5'00"	7.55	5'00"	0.00	0.00	
	10'00"	7.55	5'00"	0.00	0.00	

FIGURE 8-58

SCHOLL CANYON BARRIER PROJECT (42174A)
PERMEABILITY CALCULATIONS
EARTH MANUAL METHOD, E-18, UNSATURATED MATERIAL

BASIC DATA

BORING	BH-1	
TOP OF TEST INTERVAL (ft)	33.3	
BOTTOM OF TEST INTERVAL (ft)	39.6	
GROUNDWATER DEPTH (ft)	41.0	
RADIUS OF WELL (ft)	0.125	(Rw)
APPLIED PRESSURE (psi)	8	(Hp)
GAGE HEIGHT ABOVE SURFACE (ft)	0.0	(Hg)
STEADY STATE FLOW (gpm)	0.00	(Qc)
LENGTH OF TEST SECTION (ft)	6.3	(L)
MIDPOINT OF TEST SECTION (ft)	36.45	(He)

CALCULATIONS

54.9	H = (2.31Hp) + He
3.92	ln(L/Rw)
0.00E+00	k = [Qc/(2)(3.14)LH][ln(L/Rw)] (gpm/sq.ft.)
0.00E+00	k (cm/sec) = k (gpm/sq.ft.) * 0.0679

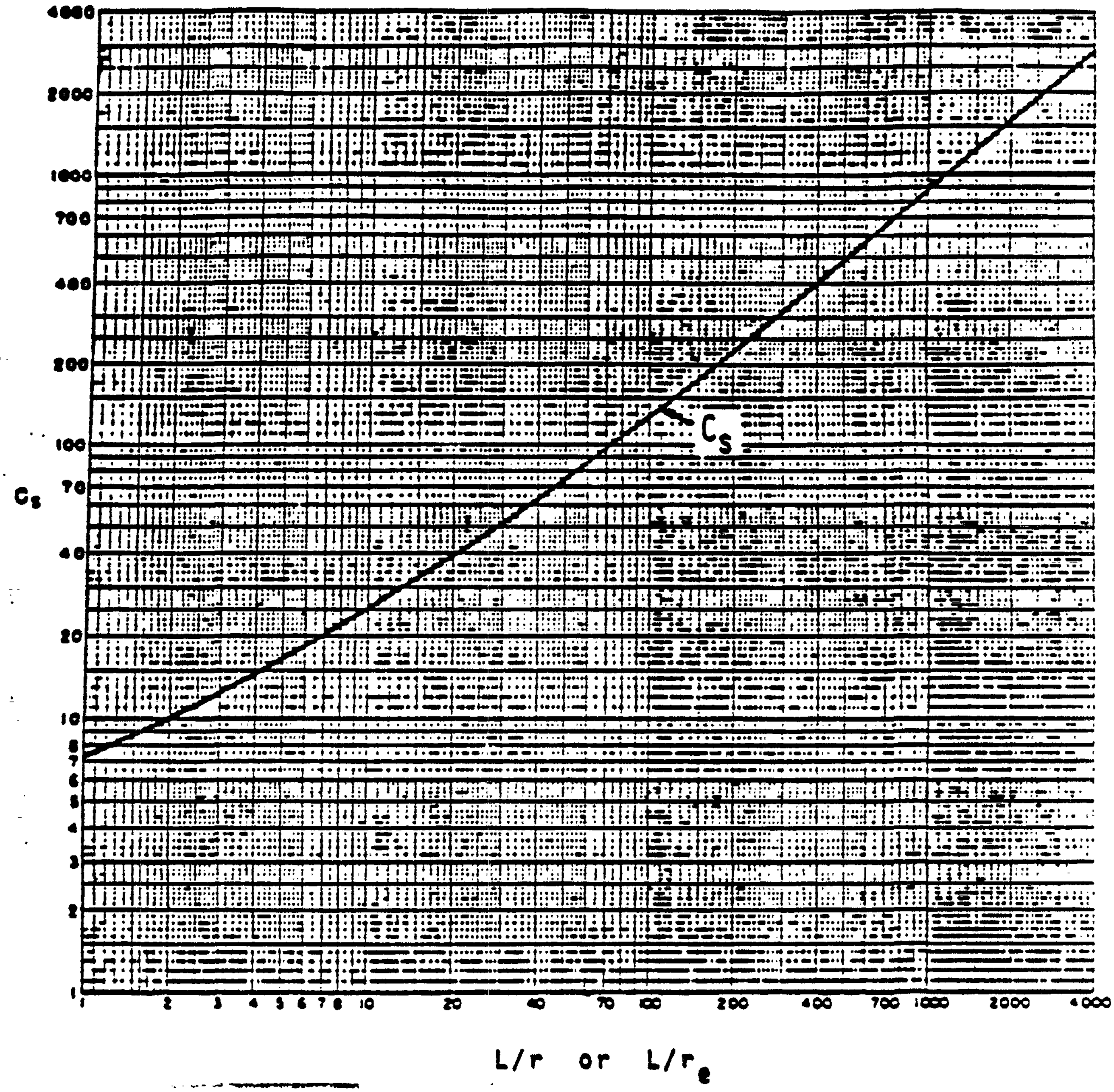
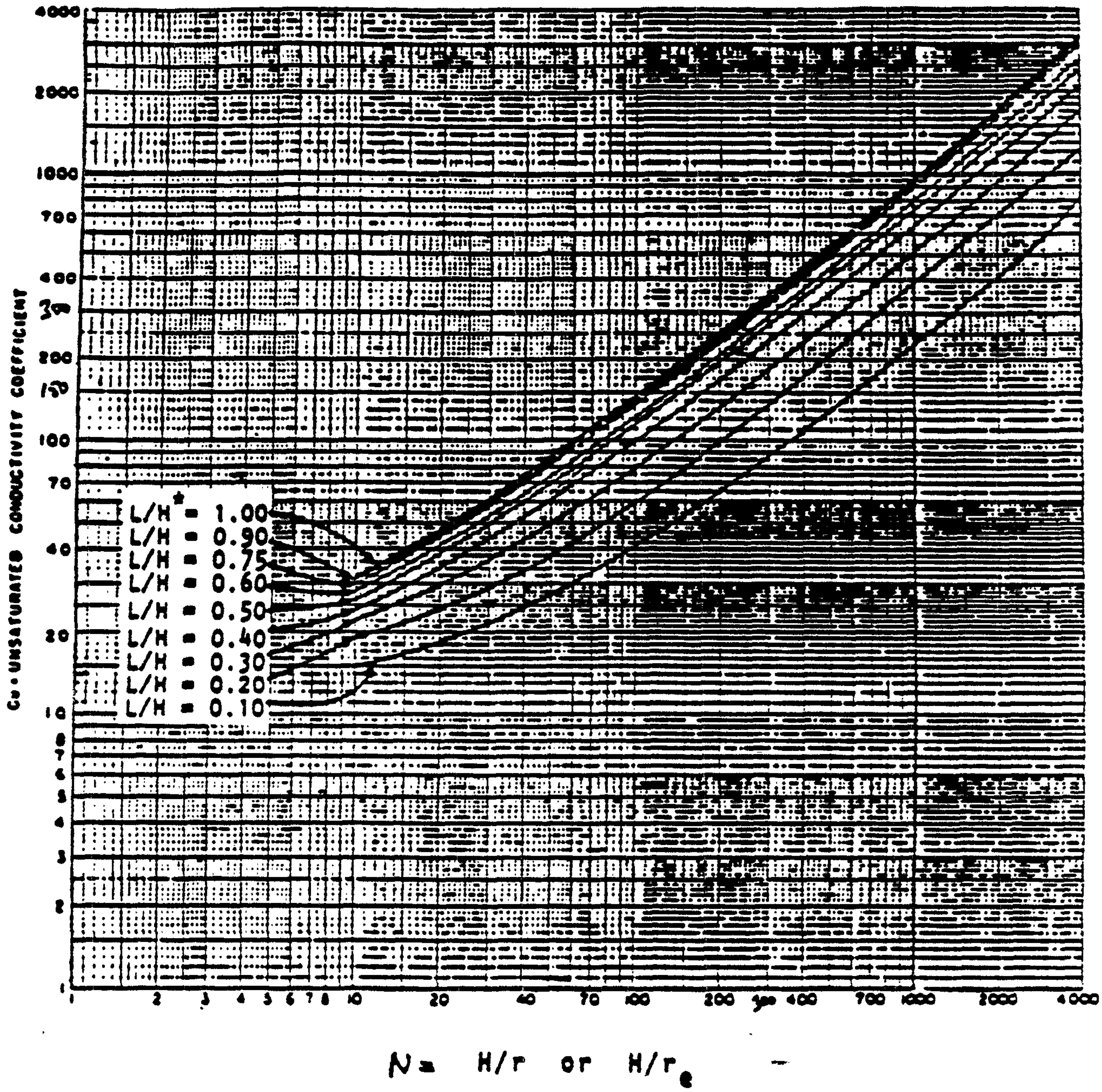


Figure 8-59 C_s VALUES FOR USBR CONSTANT HEAD TEST ANALYSIS

(USBR, G-97)



*L/H$_{elev}$ for packer tests

Figure 8-60 C_u VALUES FOR USBR CONSTANT HEAD TEST ANALYSIS (USBR, G-97)

Figures 8-51 through 8-53 require supplemental reference to Figures 8-59 or 8-60, which contain graphs for the estimation of conductivity coefficients under saturated and unsaturated conditions, respectively. For the single curve contained in Figure 8-59, an equivalent equation is presented for the well construction types in Figures 8-52 and 8-53. However, a family of curves that preclude a simplified analytic representation are contained in Figure 8-60.

Note that the USBR G-97 method for unsaturated conditions is limited in depth of application as a result of the limited range of conductivity coefficients presented in Figure 8-52. With regard to the USBR Earth Manual method, the formula is considered to be more accurate for tests below the ground water table than above it.

When using Hvorslev's method for anisotropic soils and rock, the engineer must estimate $m = K_h/K_v$. If the well is packed with gravel, the engineer must also estimate $n = K'_v/K_v$.

Where:

K_v = the estimated vertical permeability o the rock or soil mass.

K_h = the estimated horizontal permeability of the rock or soil mass.

K'_v = the vertical permeability of the gravel filter in the well (probably at least 10^{-2} cm/sec).

The values of m and n enter into the computation of the shape factor F in Figure 8-51.

Note that the USBR G-97 method for unsaturated conditions is limited in depth of application as a result of the limited range of conductivity coefficients presented in Figure 8-52. With regard to the USBR Earth Manual method, the formula is considered to be more accurate for tests below the ground water table than above it.

When using Hvorslev's method for anisotropic soils and rock, the engineer must estimate $m = K_h/K_v$. If the well is packed with gravel, the engineer must also estimate $n = K'_v/K_v$.

Where:

K_v = the estimated vertical permeability o the rock or soil mass.

K_h = the estimated horizontal permeability of the rock or soil mass.

K'_v = the vertical permeability of the gravel filter in the well (probably at least 10^{-2} cm/sec).

The values of m and n enter into the computation of the shape factor F in Figure 8-51.

LIST OF REFERENCES

LIST OF REFERENCES

Boulton, N. S., "The Drawdown of the Water-Table under Non-Steady Conditions Near a Pumped Well in an Unconfined Formation," Paper 5979 in Proceedings of the Institution of Civil Engineers, Vol. 3, p. 654, 1954.

Boulton, N. S., "Analysis of Data from Non-Equilibrium Pumping Tests Allowing for Delayed Yield from Storage," Paper 6693 in Proceedings of the Institution of Civil Engineers, Vol. 26, pp. 469-482, 1963.

Bouwer, H., Groundwater Hydrology, McGraw-Hill, 1978.

Bouwer, H., Rice, R. C., "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells," Water Resources Research, Vol. 12, No. 3, 1976.

Bredehoeft, J. D., and Papadopulos, S. S., "A Method for Determining the Hydraulic Properties of Tight Formations," Water Resources Research, Vol. 16, No. 1, pp. 233-238, 1980.

Bureau of Reclamation, U.S. Dept. of the Interior, Earth Manual, 1974.

California Department of Water Resources, Bulletin No. 118-2, Evaluation of Groundwater Resources: Livermore and Sunol Valleys; Sacramento, California, June 1974.

Cooper, Jr., H. H., Bredehoeft, J. D., and Papadopulos, S. S., "Response of a Finite-Diameter Well to an Instantaneous Charge of Water," Water Resources Research, Vol. 13, No. 1, 1967.

Cooper, Jr., H. H., and Jacob, C. E., "A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well-Field History," American Geophysical Union Transactions, Vol. 27, No. 4, pp. 526-534, 1946.

Driscoll, F. G., Editor, Ground Water and Wells, Johnson Division, UOP, Inc., St. Paul, Minnesota, 1986.

Earlougher, R. C., Advances in Well Test Analysis, Society of Petroleum Engineers of AIME, 1977.

Ferris, J. G., Knowles, D. B., "The Slug Test for Estimating Transmissivity," U.S. Geological Survey Ground Water Note 26, 1954.

Freeze, R. Allen, and Cherry, John A., Groundwater, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1979.

Gale, J. E., "A Numerical Field and Laboratory Study of Flow in Rocks with Deformable Fractures," Ph.D. Dissertation, Dept. of Civil Engineering, U.C., Berkeley, 1975.

Hantush, M. S., "Analysis of Data from Pumping Tests in Leaky Aquifers," American Geophysical Union Transactions, Vol. 37, No. 6, pp. 702-714, 1956.

Hantush, M. S., and Jacob, C. E., "Non-Steady Radial Flow in an Infinite Leak Aquifer," American Geophysical Union Transactions, Vol. 36, No. 1, pp. 95-100, 1955.

Herndon, J. Lenahan, T., Grouting in Soils, Federal Highway Administration Report RD-76-27, Vol. 1 and 2, 1976.

Hvorslev, M. J., "Time Lag and Soil Permeability in Ground-Water Observations," Bulletin No. 36, U.S. Army Corps of Engineers, p. 50, 1951.

Jacob, C. E., and Lohman, S. W., "Non-Steady Flow to a Well of a Constant Drawdown in an Extensive Aquifer," Trans. Am. Geophys. Union, Vol. 33, No. 4, 1952.

Kruseman, G. P., and DeRidder, N. A., "Analysis and Evaluation of Pumping Test Data," International Institute for Land Reclamation and Improvement, Wagenigen, The Netherlands, 1983.

Lohman, S. W., "Ground-Water Hydraulics," U.S. Geological Survey, paper 708, p. 70, 1972.

Maini, Y. N., "In-Situ Hydraulic Parameters in Jointed Rock - Their Measurement and Interpretation," Ph.D. Thesis, Imperial College of Science and Technology, London, 1971.

Milligan, V., "Field Measurement of Permeability in Soil and Rock," ASCE Proceedings, In-Situ Measurement of Soil Properties, Vol. II, 1975.

Neuman, S. P., "Theory of Flow in Unconfined Aquifers Considering Delayed Response of the Water Table," Water Resources Research, Vol. 8, No. 4, p. 1031, 1972.

Neuman, S. P., "Analysis of Pumping Test Data From Anisotropic Unconfined Aquifers Considering Delayed Gravity Response," Water Resources Research, Vol. 11, No. 2, p. 329, 1975.

Papadopulos, S. S., Bredehoeft, J. D., Cooper, Jr., H. H., "On the Analysis of Slug Test Data," Water Resources Research, Vol. 9, No. 4, 1973.

Prickett, T. A., "Type-Curve Solution to Aquifer Tests Under Water Table Conditions," Groundwater, Vol. 3, No. 3, 1965.

Schmid, W. E., "Field Determination of Permeability by the Infiltration Test," in Permeability and Capillarity of Soils, ASTM, STP 417, Am. Soc. Testing Mats, 1967.

Sherard, J. L., Woodward, R. J., Gizienski, S. F., and Clevenger, W. A., Earth and Earth-Rock Dams, J. Wiley and Sons, Inc., N.Y., 1963.

Stallman, R. W., "Aquifer-Test Design, Observation and Data Analysis," Techniques of Water Resources Investigations of the U.S. Geological Survey, Chapter B1, Government Printing Office, Washington, D.C., 1971.

Theis, C. V., "The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground Water Storage," American Geophysical Union Transactions, Vol. 16, pp. 519-524, 1935.

Todd, David K., Ground Water Hydrology, John Wiley & Sons, Second Edition, 1980.

U.S. Bureau of Reclamation, "Permeability Tests Using Drill Holes and Wells," Geology Report G-97, 1951.

U.S. Department of the Interior, Ground Water Manual, U.S. Government Printing Office, Washington, D.C., 1981.

Walton, William C., "Selected Analytical Methods for Well and Aquifer Evaluation," Illinois State Water Survey Bulletin, 49, 1962.

Walton, William, C., Groundwater Resource Evaluation, McGaw-Hill, 1970.

Woodward-Clyde Consultants, Permeability Test Methods with Applications to Solution Mining - Final Report - U.S. Bureau of Mines, Project #13719A, 1977.

APPENDIX A

USEFUL CONVERSION TABLES

RANGE OF HYDRAULIC CONDUCTIVITY VALUES

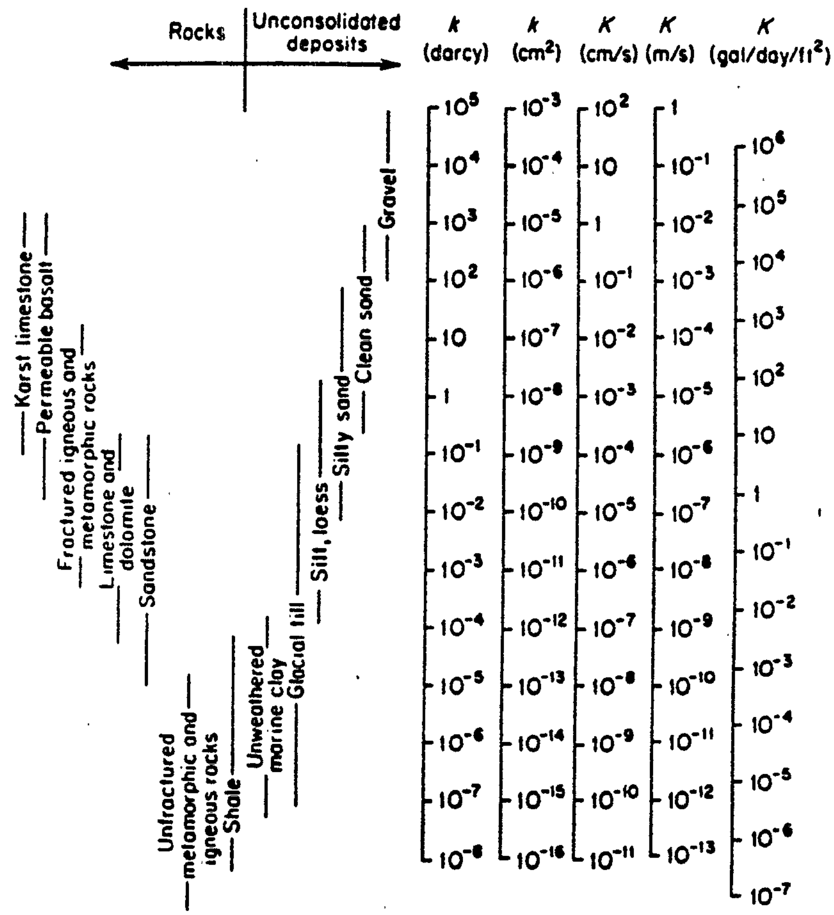


Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

	Permeability, k*			Hydraulic conductivity, K		
	cm²	ft²	darcy	m/s	ft/s	gal/day/ft²
cm²	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft²	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	5.74×10^{5}
gal/day/ft²	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.74×10^{-6}	1

*To obtain k in ft², multiply k in cm² by 1.08×10^{-3}.

From Freeze and Cherry (1979)

APPENDIX A.
Conversion Tables

Length

Unit	Equivalent[1,2]					
	millimeters	inches	feet	meters	kilometers	miles
millimeters	1	3.937×10^{-2}	3.281×10^{-3}	1×10^{-3}	1×10^{-6}	6.214×10^{-7}
inches	25.4	1	8.33×10^{-2}	2.54×10^{-2}	2.54×10^{-5}	1.578×10^{-5}
feet	304.8	12	1	0.3048	3.048×10^{-4}	1.894×10^{-4}
meters	1,000	39.37	3.281	1	1×10^{-3}	6.214×10^{-4}
kilometers	1×10^{6}	3.937×10^{4}	3,281	1,000	1	0.6214
miles	1.609×10^{6}	6.336×10^{4}	5,280	1,609	1.609	1

Area

Unit	Equivalent[1,2]						
	square inches	square feet	square meters	acres	hectares	square kilometers	square miles
square inches	1	6.944×10^{-3}	6.452×10^{-4}	1.594×10^{-8}	6.452×10^{-8}	6.452×10^{-10}	2.491×10^{-10}
square feet	144	1	9.29×10^{-2}	2.296×10^{-5}	9.29×10^{-9}	9.29×10^{-8}	3.587×10^{-8}
square meters	1,550	10.76	1	2.471×10^{-4}	1×10^{-4}	1×10^{-6}	3.861×10^{-7}
acres	6.273×10^{6}	4.356×10^{4}	4,047	1	0.4047	4.047×10^{-3}	1.563×10^{-3}
hectares	1.55×10^{7}	1.076×10^{5}	1×10^{4}	2.471	1	0.01	3.861×10^{-3}
square kilometers	1.55×10^{9}	1.076×10^{7}	1×10^{6}	247.1	100	1	0.3861
square miles	4.014×10^{9}	2.788×10^{7}	2.59×10^{6}	640	259	2.59	1

Volume

Unit	Equivalent[1,2]						
	cubic inches	liters	gallons	cubic feet	cubic yards	cubic meters	acre-ft
cubic inches	1	1.639×10^{-2}	4.329×10^{-3}	5.787×10^{-4}	2.143×10^{-5}	1.639×10^{-5}	1.329×10^{-8}
liters	61.02	1	0.2642	3.531×10^{-2}	1.308×10^{-3}	0.001	8.106×10^{-7}
gallons	231.0	3.785	1	0.1337	4.951×10^{-3}	3.785×10^{-3}	3.068×10^{-6}
cubic feet	1,728	28.32	7.481	1	3.704×10^{-2}	2.832×10^{-3}	2.296×10^{-5}
cubic yards	4.666×10^{4}	764.6	202.0	27	1	0.7646	6.198×10^{-4}
cubic meters	6.102×10^{4}	1,000	264.2	35.31	1.308	1	8.106×10^{-4}
acre-ft	7.527×10^{7}	1.233×10^{6}	3.259×10^{5}	4.356×10^{4}	1,613	1,233	1

Discharge (flow rate, volume/time)

Unit	Equivalent[1,2]				
	gallons per minute	liters per second	acre-feet per day	cubic feet per second	cubic meters per day
gallons per minute	1	6.309×10^{-2}	4.419×10^{-3}	2.228×10^{-3}	5.45
liters per second	15.85	1	7.005×10^{-2}	3.531×10^{-2}	86.4
acre-feet per day	226.3	14.28	1	0.5042	1,234
cubic feet per second	448.8	28.32	1.983	1	2,447
cubic meters per day	1.369×10^{9}	8.64×10^{7}	6.051×10^{6}	3.051×10^{6}	1

Slot size	inches	millimeters
4	0.004	0.102
6	0.006	0.152
8	0.008	0.203
10	0.010	0.254
12	0.012	0.305
15	0.015	0.381
18	0.018	0.457
20	0.020	0.508
25	0.025	0.635
30	0.030	0.762
35	0.035	0.889
40	0.040	1.016
45	0.045	1.143
50	0.050	1.270
60	0.060	1.524
70	0.070	1.778
80	0.080	2.032
90	0.090	2.286
100	0.100	2.540
125	0.125	3.175
150	0.150	3.810
175	0.175	4.445
200	0.200	5.080
225	0.225	5.715
250	0.250	6.350

Equations for areas and volumes

Circumference of circle = 3.1416 × dia = 6.2832 × radius
Area of circle = 0.7854 × $(\text{dia})^2$ = 3.1416 × $(\text{radius})^2$
Area of sphere = 3.1416 × $(\text{dia})^2$
Volume of sphere = 0.5236 × $(\text{dia})^3$
Area of triangle = 0.5 × base × height
Area of trapezoid = 0.5 × sum of the two parallel sides × height
Area of square, rectangle, or parallelogram = base × height
Volume of pyramid = area of base × 1/3 height
Volume of cone = 0.2618 × $(\text{dia of base})^2$ × height
Volume of cylinder = 0.7854 × height × dia

[1]Equivalent values are shown to 4 significant figures.

[2]Multiply the value of the given unit by the equivalent value shown to obtain the numerical amount of the equivalent unit.

[3]Water at 68°F (20°C).

[4]Mercury at 32°F (0°C).

300367

APPENDIX B

SUMMARY OF SUPPLEMENTARY AQUIFER ANAYTICAL TECHNIQUES

(Kruseman and DeRidder, 1983)

TABLE 2 · ANALYTICAL TECHNIQUES FOR SIMPLE CONDITIONS: From Kruseman and DeRidder (1983)

MAIN ASSUMPTIONS: 1. The aquifer has apparently infinite areal extent; 2. The aquifer is homogeneous, isotropic and uniform thickness; 3. Prior to pumping the piezometric surface and phreatic surface are (nearly) horizontal; 4. The discharge rate is constant; 5. The aquifer is fully penetrated. *For unsteady-state methods only*: 6. The storage in the well can be neglected; 7. Water removed from storage is discharged unstantaneously with decline of head (not valid for unconfined aquifers with delayed yield and for semi-unconfined aquifers).

Aquifer type	Type of solution	Flow equation	Method of analysis: name	Method of analysis: type	Remarks	Calculated parameters	Section	Reference
confined	steady state	$Q = \frac{2\pi kD(s_1 - s_2)}{\ln(r_2/r_1)}$	Thiem	calculation		kD	1.1	Thiem, 1906
	unsteady-state	$s = \frac{Q}{4\pi kD}\int_u^\infty \frac{e^{-y}}{y}dy = \frac{Q}{4\pi kD}W(u)$	Theis	curve fitting	$u = \frac{r^2S}{4kDt}$	kD and S	2.1	Jacob, 1940
			Chow	nomogram		kD and S	2.2	Chow, 1952
		$s = \frac{2.30Q}{4\pi kD}\log\frac{2.25kDt}{r^2S}$	Jacob	straight line	$\frac{r^2S}{4kDt} < 0.01$	kD and S	2.3	Cooper and Jacob, 1946
		$s' = \frac{2.30Q}{4\pi kD}\log\frac{t}{t'}$	Theis recovery	straight line	s' = residual drawdown; t' time since pumping stopped	kD	2.4	Theis, 1935
semi-confined	steady-state	$s_m = \frac{Q}{2\pi kD}K_0\left(\frac{r}{L}\right)$	De Glee	curve fitting	$L > 3D$	kD and c	3.1	De Glee, 1930
		$s_m = \frac{2.30Q}{2\pi kD}\left(\log 1.12\frac{L}{r}\right)$	Hantush Jacob	straight line	$r/L < 0.05$	kD and c	3.2	Hantush and Jacob, 1955
		$Q - Q' = \frac{2\pi kD(s_1 - s_2)}{\ln(r_2/r_1)}$	Ernst mod. Thiem meth.	calculation	Q' = recharge rate by confining layer	kD	3.3	oral communication
	unsteady-state	$s = \frac{Q}{4\pi kD}\int_u^\infty \frac{1}{y}\exp\left(-y - \frac{r^2}{4L^2y}\right)dy =$	Walton	curve fitting	$u = \frac{r^2S}{4kDt}$	kD, S and c	4.1	Walton, 1962
		$= \frac{Q}{4\pi kD}W(u, r/L)$	Hantush I	inflection point		kD, S and c	4.2	Hantush, 1956
			Hantush II	inflection point		kD, S and c	4.3	Hantush, 1956
		$s = \frac{Q}{4\pi kD}[2K_0(r/L) - W(q, r/L)]$	Hantush III	curve fitting	$q = \frac{kDt}{SL^2}$; $q > \frac{2r}{L}$; $t > 4t_p$	kD, S and c	4.4	Hantush, 1956
unconfined with delayed yield	unsteady-state	$s = \frac{Q}{4\pi kD}\int_0^\infty 2J_0\left(\frac{r}{B}y\right)\frac{y^2}{y^2+1}\cdot$	Boulton	curve fitting	y = variable of integration			
and semi-unconfined		$\cdot\{1 - \exp[-\alpha t y/(y^2+1)]\}\frac{dy}{y} =$			$u_A = \frac{r^2S_A}{4kDt}$; $u_Y = \frac{r^2S_Y}{4kDt}$	kD, S_A, S_Y, B and $1/\alpha$	5.1	Boulton, 1963
		$= \frac{Q}{4\pi kD}W(u_{AY}, r/B)$			$\gamma = (S_A + S_Y)/S_A$; $\gamma > 100$			
unconfined	steady-state	$Q = \pi k\frac{h_2^2 - h_1^2}{\ln(r_2/r_1)} = \frac{2\pi kD(s'_{m1} - s'_{m2})}{\ln(r_2/r_1)}$	Thiem-Dupuit	calculation	$s' = s - (s^2/2D)$	kD	6.1	Thiem, 1906
	unsteady-state	as for confined aquifers			s is replaced by $s' = s - (s^2/2D)$	kD and, generally, S	7 and 2.1 to 2.4	Thiem, 1906; Jacob, 1940; Chow, 1952; Cooper and Jacob, 1946

300369

TABLE 3 - ANALYTICAL TECHNIQUES FOR MORE COMPLEX CONDITIONS

Procedure

The well is shut down for a period long enough for the pressure to become static (to be measured with a pressure gauge fitted at the top of the well). Then the well is opened up again and the discharge rate is measured at intervals of from 30 to 60 seconds during the first minutes and afterwards with gradually increasing intervals. The analysis follows the pattern of the Jacob method (see Chapter 3, Section 2.3).

- Plot the values of s_w/Q versus t on single logarithmic paper (t on logarithmic scale). Fit a straight line through the plotted points. Extend this straight line till it intercepts the time-axis where $s_w/Q = 0$ at the point t_0.
- Introduce the value of the slope of the line $\Delta(s_w/Q)$, i.e. the difference of s_w/Q per log cycle of t into Eq. (174) and solve for kD

$$kD = \frac{2.30}{4\pi\Delta(s_w/Q)} \tag{174}$$

- Calculate the storage coefficient, S, from

$$S = \frac{2.25kDt_0}{r_w^2} \tag{175}$$

Table 17. REVIEW OF METHODS of analysis presented in Chapter 4.

MAIN ASSUMPTIONS (if replaced this is mentioned in column 1): 1. The aquifer has apparently infinite areal extent; 2. The aquifer is homogeneous, and isotropic and of uniform thickness; 3. Prior to pumping, the piezometric surface and/ or phreatic surface are (nearly) horizontal; 4. The discharge rate is constant; 5. The aquifer is fully penetrated. *For unsteady state methods only:* 6. The storage in the well can be neglected; 7. Water removed from storage is discharged instantaneously with decline of head.

Replaced assumption(s)	Aquifer type	Type of solution	Method of name	Analysis type	Remarks	Calculated parameters	Section	Reference
1. aquifer crossed by one or more fully penetrating recharge or barrier boundaries	confined or unconfined	steady-state	Dietz	calculation	recharge boundaries only.	kD	1.1.1	DIETZ, 1943
		unsteady-state	Stallman	curve fitting	recharge and/or barrier boundaries	kD and S	1.2.1	FERRIS, et al., 1962
			Hantush image	straight line	one recharge boundary	kD and S	1.2.2	HANTUSH, 1959
2. aquifer homogeneous, anisotropic and of uniform thickness	confined or unconfined	unsteady-state	Hantush	calculation		$(kD)_x$, $(kD)_y$ and S	2.1.1	HANTUSH, 1966
			Hantush-Thomas	calculation	for recovery data also	$(kD)_x$, $(kD)_y$ and S	2.1.2	HANTUSH and THOMAS, 1966
	semi-confined	unsteady-state	Hantush	calculation		$(kD)_x$, $(kD)_y$, S and c	2.2.1	HANTUSH, 1966
2. aquifer homogeneous and isotropic; but thickness varies exponentially	confined	unsteady-state	Hantush	curve fitting	$dD/dx < 0.20$	kD_0 and S	3.1.1	HANTUSH, 1964
3. prior to pumping the phreatic surface slopes in the direction of flow	unconfined	steady-state	Culmination point	calculation		kD	4.1.1	oral communication
		unsteady-state	Hantush	curve fitting	$i < 0.20$	kD and S	4.2.1	HANTUSH, 1964
4. discharge rate variable	confined or unconfined	unsteady-state	Cooper-Jacob	straight line	step-type pumping	kD and S	5.1.1	COOPER and JACOB, 1946
			Aron-Scott	straight line	continuously decreasing discharge	kD and S	5.2.1	ARON and SCOTT, 1965
			Sternberg	straight line	continuously decreasing discharge	kD and S	5.2.2.	STERNBERG, 1968
			Sternberg recovery	straight line	continuously decreasing discharge	kD	5.2.3	STERNBERG, 1967

TABLE 3 (CONTINUED) - ANALYTICAL TECHNIQUES FOR MORE COMPLEX CONDITIONS

Replaced assumption(s)	Aquifer type	Type of solution	Method of name	Analysis stype	Remarks	Calculated parameters	Section	References
5. the pumped well is partially penetrating	confined	steady-state	Huisman correction I	calculation	$r > r_w$	kD	6.1.1	ANONYMOUS, 1964
			Huisman correction II	calculation	$r = r_w$	kD	6.1.2	ANONYMOUS, 1964
			Jacob correction	calculation	screened part near top or near bottom of the aquifer	kD	6.1.3	JACOB, 1963
	semi-confined	steady-state	Huisman correction I and II	calculation		kD	6.2.1	ANONYMOUS, 1964
	unconfined	steady-state	Hantush correction	calculation		kD	6.3.1	HANTUSH, 1964
	confined	unsteady-state	Hantush mod. Theis method	curve fitting	short period of pumping	k, S and D	6.4.1	HANTUSH, 1962
			Hantush mod. Jacob method	straight line	long period of pumping	kD and S	6.4.2	HANTUSH, 1962
6. storage in the well cannot be neglected	confined	unsteady-state	Papadopulos-Cooper	curve fitting	entrance resistance is zero	kD and S	7.1.1.	PAPADOPULOS and COOPER, 1967
2. and 5. two-layered aquifer with semi-pervious dividing layer	semi-confined	steady-state	Huisman-Kemperman	nomogram and curve fitting	only upper part is pumped	k_1D_1, k_2D_2, c_1 and c_2	8.1.1	HUISMAN and KEMPERMAN, 1951
			Bruggeman	straight line	upper- and lower part are pumped separately	k_1D_1, k_2D_2, c_1 and c_2	8.1.2	BRUGGEMAN, 1966
added assumption: the entrance resistance of the pumped well is zero	confined	steady-state	Logan	calculation	approximation method without piezometers	kD	9.1.1	LOGAN, 1964
			Gosselin	calculation	approximation method without piezometers for very deep aquifers	kD	9.1.2	GOSSELIN, 1951
	unconfined	steady-state	Logan	calculation	approximation method without piezometers	kD	9.2.1	LOGAN, 1964
added assumption as above and 5. the pumped well is partially penetrating	confined	steady-state	Zangar	calculation	approximation method without piezometers	k	9.3.1	ZANGAR, 1953
added assumptions: the entrance resistance of the pumped well is zero; the value of S is known.	confined	unsteady-state	Hurr	calculation	approximation method without piezometers	kD	9.4.1	HURR, 1966
	unconfined	unsteady-state	Hurr	calculation	approximation method without piezometers	kD	9.5.1	HURR, 1966
well is free flowing: drawdown constant, discharge variable	confined	unsteady-state	Jacob-Lohman	straight line		kD and S	10.1.1	JACOB and LOHMAN, 1952

From Kruseman and DeRidder (1983)

APPENDIX C

CROSS-INDEX OF EARLY LITERATURE ON PUMPING TESTS

(Stallman, 1971)

SITE CONDITIONS TREATED AND SUBJECT EMPHASIS IN SELECTED LITERATURE ON PUMPING TESTS

[x, condition treated in this paper; o, artesian storage release assumed to be zero]

Category	Artesian aquifer			Horizontal plane anisotropy				Partial penetration			Well characteristics						Vertical flow components, unconfined			Delayed yield, unconfined				Variable Q			Miscellaneous			
	Thiem (1906)	Theis (1935)	Hantush (1960)	Hantush (1966a)	Hantush (1966b)	Hantush and Thomas (1966)	Papadopulos (1967)	Hantush (1961a)	Hantush (1961d)	Weeks (1964)	Jacob (1947)	Rorabaugh (1953)	Cooper and others (1965)	Bredehoeft and others (1966)	Cooper and others (1967)	Papadopulos and Cooper (1967)	Boulton (1954a)	Stallman (1965)	Norris and Fidler (1966)	Boulton (1954b)	Boulton (1963)	Boulton (1964)	Prickett (1965)	Jacob and Lohman (1952)	Ferris and others (1962)	Hantush (1964b)	Hantush (1962)	Hantush and Papadopulos (1962)	Rixel and others (1963)	Boulton (1965)
A. Type of control imposed:																														
Step change Q	x	x	x	x	x	x	x	x	x	x	x	x	--	--	--	x	x	x	x	x	x	x	x	--	--	--	x	x	x	--
Step change s	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	x
Pulsed Q	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pulsed s	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Variable Q	--	--	--	--	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	x	--	--	--	--
Variable s	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
B. Control-well characteristics:																														
Full penetration	x	x	x	x	x	x	x	--	--	--	x	x	x	x	x	x	x	x	--	x	x	x	x	x	x	x	x	--	x	x
Partial penetration	--	--	--	--	x	--	--	x	x	x	--	--	--	--	--	--	--	x	x	--	--	--	--	--	--	--	--	x	--	--
Diameter infinitesimal	x	x	x	x	x	x	x	x	x	x	x	x	--	--	--	--	x	--	x	x	x	x	x	--	x	x	x	--	x	--
Diameter finite	--	--	--	--	--	--	--	--	--	--	--	--	x	x	x	x	--	x	--	--	--	--	--	--	--	x	x	--	--	x
Seepage face	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x
Well loss	--	--	--	--	--	--	--	--	--	--	x	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Radial screens	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--
C. Conductivity and flow conditions:																														
Homogeneous, isotropic	x	x	x	--	--	--	--	x	x	--	x	x	x	x	x	x	x	x	--	x	x	x	x	x	x	x	--	x	x	--
Homogeneous, anisotropic	--	--	--	x	x	x	x	--	--	x	--	--	--	--	--	--	--	x	x	--	--	--	--	--	--	--	--	--	--	x
Heterogeneous, isotropic	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--
Permeable confining beds (nonsteady)	--	--	x	x	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--
Sloping beds	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--
Areally infinite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	--	x	x	x	x	--	x	x	x	x	--	x
Areally semi-infinite	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	--	--	x	x	--	--
Areally discontinuous	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--
Dewatering negligible	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	--	x	x	x	x	--	x	x	x	x	x	x
Dewatering significant	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	--	--	--	--	--	--
Flow radial	x	x	x	x	x	x	x	--	--	--	x	x	x	x	x	x	--	--	--	x	x	x	x	x	x	x	x	--	x	--
Flow radial and vertical	--	--	--	--	--	--	--	x	x	x	--	--	--	--	--	--	x	x	x	--	--	--	--	--	--	--	--	x	--	x
Nonsteady flow	--	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Steady flow	x	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
D. Storage relation:																														
Linear to head	--	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	--	--	--	--	x	x	x	x	x	x	--
Head and time	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	x	x	x	--	--	--	--	--	--	--
Artesian	--	x	x	x	x	x	x	x	x	--	x	x	x	x	x	x	o	o,x	o	o	o	--	--	x	x	x	x	x	x	o
Unconfined	--	--	--	--	--	--	--	--	--	x	--	--	--	--	--	--	x	x	x	x	x	x	x	--	--	--	--	x	--	x
E. Emphasis of paper:																														
Q versus time	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	x	x	x	--	--	--	x
s versus time and space	--	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	--	x	x	x	--	--	x	x	x	x	x	--
Analytical equation	x	x	x	x	x	x	x	x	--	--	x	x	x	x	x	x	x	--	--	x	x	x	--	--	--	x	x	x	x	x
Graphical type curve	--	--	x	--	--	--	--	x	--	--	--	--	x	x	x	x	x	x	--	--	x	--	--	x	--	x	--	--	x	x
Tables, type-curve	--	[1]	x[2,3]	--	--	--	--	x	--	--	--	--	--	--	x	x	x	--	--	--	x	x	--	--	--	x	--	--	--	x
Analog computer	--	--	--	--	--	--	--	--	--	--	--	--	--	x	--	x	--	x	--	--	--	--	--	--	--	--	--	--	--	--
Theory development	x	x	x	x	x	x	x	x	--	--	x	x	x	x	x	x	x	x	--	x	x	x	--	x	x	x	x	x	x	x
Application of data	--	--	--	x	--	x	x	--	x	x	x	x	--	--	x	--	--	--	x	x	x	x	x	--	--	x	--	--	x	--

[1] Ferris and others (1962).

[2] Hantush (1961b).

[3] Hantush (1961c).

From Stallman (1971)

NO. 12

SOIL GAS SAMPLING AND ANALYSIS

WOODWARD-CLYDE CONSULTANTS
HAZARDOUS WASTE MANAGEMENT PRACTICE
TECHNICAL MEMORANDUM NO. 12

SOIL GAS SAMPLING AND ANALYSIS

REVISION 0

MARCH 1987

300375

TABLE OF CONTENTS

TECHNICAL MEMORANDUM NO. 12
SOIL GAS SAMPLING AND ANALYSIS

HAZARDOUS WASTE MANAGEMENT PRACTICE

TECHNICAL MEMORANDUM NO. 12
SOIL GAS SAMPLING AND ANALYSIS

12.1 Introduction

12.1.1 Purpose

The purpose of this document is to provide guidance on the selection of equipment and procedures used in collecting and analyzing soil gas. Technical Memorandum No. 12 will cover both conventional soil gas investigations and the screening of soil samples via headspace analysis techniques. Various methodologies for conducting soil gas and soil headspace analyses are currently being practiced by WCC personnel at different offices. This document is not intended to endorse any particular method of soil gas sampling, but rather to provide a set of criteria upon which to assess the reliability and applicability of the methods which are selected.

Soil gas investigations can be performed using either relatively inexpensive field instruments and hand-driven probes or sophisticated laboratory equipment and mechanically-driven probes. The availability of specialized equipment and/or subcontractors will determine, in part, the options which are available for a particular project. Pertinent site-specific and compound-specific factors which influence the collection and interpretation of soil gas data are identified in this memorandum.

12.1.2 Defining Soil Gas Sampling

Soil gas sampling describes the collection and analysis of the soil air phase as a means of delineating subsurface contamination by volatile organic chemicals (VOC's). Soil gas or vapor monitoring techniques utilize an in-situ gas analysis or sample collecting device which is installed beneath the ground surface. The presence of VOC's in soil gas indicates that there is contamination from the observed compounds either in soil near the device or in groundwater below it. Results are used to select the locations for groundwater monitoring wells and/or soil borings. Soil gas investigations can also be used to distinguish between soil and groundwater contamination, to identify sources of VOC's, and to locate leaks in underground tanks and pipelines.

Soil vapor analysis can be used to estimate soil contamination by monitoring the headspace vapors associated with soil samples. Volatile contaminants in the headspace above soil samples in a sealed container indicate the presence of VOC's in the liquid, solid, gas or organic fraction of soils. The results of headspace analyses are used to screen soil contamination in the field (e.g., to determine the volume of soil which must be removed or treated) and to select samples for laboratory analyses.

12.1.3 Theory of Vapor Phase Dynamics

In order to effectively design soil gas surveys and interpret their results, the subsurface transport and fate of VOC's should be considered. These factors can have a significant effect on the presence and concentration of VOC's in the soil atmosphere. Both physical and microbiological processes can influence soil gas investigations.

Partitioning between gaseous and aqueous phases is the physical process which permits groundwater contaminants to be detected in soil gas. The air-water partitioning coefficient can be dependent on both the vapor pressure and aqueous solubility of a compound, which is described by Henry's Law constant (Figure 12-1). Generally, low molecular weight organic compounds (i.e., hydrocarbons, halogenated hydrocarbons, ketones) are most readily detected in soil gas. Henry's Law constants are simply a ratio of compound's vapor pressure to its aqueous solubility. These constants can be calculated according to the method described in MacKay and Shiu (1981). Compounds possessing Henry's Law constants less than 0.05 to 0.1 kPa m^3/mol tend to remain dissolved in groundwater or soil moisture and are often difficult to detect in soil gas samples.

Figure 12.2 lists the Henry's Law Constants and vapor pressures for some common organic chemicals. Compounds possessing vapor pressures less than 1 mm Hg at 25°C will probably not be detected in soil gas, irrespective of their Henry's Law Constant. Vapor pressures provide an estimate of the diffusion coefficient and, thus, the "mobility" of the compound in the gas phase. Polycyclic aromatic hydrocarbons, such as anthracene, appear to have a favorable partitioning coefficient, but will not diffuse appreciably in the gas phase. By contrast, MEK has a high vapor pressure but is often absent from soil gas because it remains solubilized in the aqueous phase of the soil.

Once VOC's enter the soil gas, they diffuse in response to a chemical concentration gradient. According to steady state models, vertical contaminant flux is proportional to the air-filled porosity of the vadose zone, the VOC diffusion coefficient, and the gas phase concentration gradient. If groundwater contamination represents the principal source of VOC's in soil gas and the ground surface acts as a VOC sink, then diffusion of VOC's is predominantly in a vertical direction. If the source of VOC's is a leaking tank or surface spill, then lateral diffusion will dominate within a finite radius of the vadose zone source. A typical VOC concentration profile with depth is shown in Figure 12-3.

Headspace analysis of soil samples can be a useful screening tool, however, VOC concentrations in headspace are affected by the complexities of gas phase equilibrium. As soil samples are agitated in a closed container, VOC's present in the soil gas matrix (air-filled pores) are released to the headspace. In addition, VOC's associated with the aqueous, organic or solid phases of the matrix are free to establish a new equilibrium with the surrounding air. The reliability of headspace analysis in predicting concentrations of extractable organic compounds is highly dependent on contaminant properties and soil conditions.

12.1.4 Applications of Soil Gas Sampling

Soil gas investigations have been used to assist in performing the following tasks:

- o delineating the areal extent of VOC plumes in groundwater;
- o delineating the lateral and vertical extent of VOC contamination in soils;
- o locating the source of VOC contamination in soil or groundwater;
- o assessing the chemical composition of subsurface contaminant plumes (VOC's only);
- o locating leaks in underground tanks and pipelines;
- o selecting locations for monitoring wells and soil borings; and
- o measuring the accumulation of certain explosive or toxic gases under buildings or other structures.

Headspace analysis of soil samples can be used to assist in the following activities:

- o detecting the presence of contaminated zones in soil during drilling operations;
- o estimating the volume of soil which must be removed from a contaminated site;
- o assessing whether soil samples collected in geotechnical investigations are contaminated;
- o selecting soil samples which are submitted for laboratory analysis; and
- o assessing the possible health and safety hazards associated with working in contaminated soils.

Soil gas measurements usually represent an indirect measure of the parameter of interest (e.g., groundwater plumes, extractable hydrocarbon concentrations in soil, sources of subsurface leaks). Therefore, the interpretation of data collected from these investigative or monitoring activities is often as critical as the field sampling procedures.

12.2 Subsurface Sampling

12.2.1 Soil Gas Sampling Methodologies

The sampling of VOC's in soil gas may be accomplished by either passive or dynamic (grab) techniques. Passive samplers generally represent the least expensive and simplest application of the soil gas methodologies. Passive sampling techniques utilize an in-situ adsorbent (usually activated charcoal) which is buried in the soil and allowed to remain undisturbed for a period of days to weeks. The adsorbent is then retrieved from the soil and transported to a laboratory where VOC's are desorbed and analyzed by gas chromatography or mass spectrometry.

Dynamic or grab sampling techniques require the installation of a probe or soil boring in the vadose zone followed by withdrawal of soil gas with an air pump. The simplest version of grab sampling is performed by installing a small diameter tube down an augered borehole. The tube is sealed at the ground surface and soil gas is drawn up the small diameter conduit where it can be sampled at the surface. Soil gas can then be analyzed on-site by portable analytical instruments such as a Photovac gas chromatograph, a Century Systems organic vapor analyzer (OVA), or a Thermo Electron organic vapor meter (OVM).

An alternative grab sampling technique requires a small volume of soil gas to be pumped through a hollow probe which is typically driven several feet into the ground. During the pumping phase, an aliquot of soil gas is collected with a syringe and immediately injected into a gas chromatograph mounted in a field vehicle. Alternatively, soil gas can be pumped through a charcoal or Tenax trap and then desorbed and analyzed in a manner similar to that for passive samplers.

12.2.2 Soil Gas Sampling Equipment

Passive sampling can be most cost-effectively conducted using activated carbon organic vapor monitors such as those manufactured by 3M. These vapor monitors, which can be purchased for approximately $10 each, are suspended in a metal can or other container which is then buried upside-down in the soil. The passive samplers should be buried at least 2 feet deep in order to prevent dilution of soil gas with atmospheric air. Instructions for exposing and collecting the samplers are specified by the manufacturer. A review of this method has been presented by Kerfoot and Mayer (1986).

The exposure time for passive samplers is estimated by a combination of the adsorbent capacity for individual compounds and their estimated concentration in soil gas. Passive samplers are analyzed by desorbing the charcoal with a solvent and determining the VOC concentration in solution. Sampling time and mean accumulation rate for indiviudal compounds are then used to calculate the average VOC concentration in soil gas over the sampling period. Passive samplers can also estimate VOC flux in soil gas provided that the sampling rate of the adsorbent is not exceeded by the contaminant flux. A typical passive sampler is shown in Figure 12-4.

Grab sampling techniques require that a soil gas probe be driven at least 3 feet below the ground surface. The probes are usually constructed of 1/4 to 1 inch diameter steel pipe and equipped with either perforations near the tip or a detachable drive point (Figure 12-5). A small amount of soil gas (less than 10 liters) is then pumped from the subsurface and collected from the evacuation line or a syringe port. If soil gas sampling is performed in augered boreholes, the probe or sampling device should be driven at least 2 feet below the bottom of the boring. Gas sampling instruments should not be lowered down open boreholes as a means of analyzing soil gas. Such analyses represent an unknown mixture of soil gases and atmospheric air.

Probe driving can be completed with either mechanical (hydraulic or pneumatic) or manual equipment. Moreover, either electric or battery-operated pumps are appropriate for withdrawing samples. A vacuum gauge or flow meter should be installed on the pump in order to determine whether the air-filled porosity of the soil is sufficient to withdraw a representative sample. The vacuum pressure at which soil gas samples are collected should be recorded for each sampling location.

12.2.3 Investigation Approaches

Generally, soil gas sampling is most effective for highly volatile compounds (e.g., Henry's Law Constants above 0.1 kPa m^3/mol and vapor pressures above 1 mm Hg) and coarse dry soils. A minimum air-filled porosity of 5 percent is normally required to obtain a representative soil gas sample. Increasing soil moisture (particularly in fine-grained soils) significantly affects soil gas sampling because gas-filled pores become discontinuous and because there is a mass transfer of VOC's from the gaseous to the aqueous phase (Figure 12-6). Similarly, the organic fraction of soils (e.g., natural organic debris or immiscible product layers) may act as a sink for gas phase VOC's. Pavement, clay layers, and perched water zones act as barriers to gaseous diffusion and should be identified, if possible, prior to the design of a soil gas investigation.

The presence of underground utilities should also be considered when evaluating whether soil gas sampling is an appropriate technology at specific sites. Obviously, the location of subsurface utilities should be documented in order to avoid the physical hazards associated with driving probes through utility conduits. Additionally, cracks or junctions in sewer and natural gas lines can release volatile compounds into soil gas which often mask the regional subsurface contaminant plume. Utility trenches can act as conduits for laterally diffusing VOC's as a result of backfill materials, which often have a relatively high air permeability compared to undisturbed soils.

Sampling along an established grid is recommended at a site where the sources or general orientation of a subsurface contaminant plume are unknown. However, if data are available which identify the source areas or plume characteristics (e.g., existing monitoring wells or soil borings), then sampling on a grid system is probably inefficient. Instead, delineation of plume edges is most efficiently achieved by establishing a transect parallel to the direction of groundwater flow and sampling outward from the suspected source. Once an initial boundary point is identified, subsequent sampling locations can be selected on the basis of real-time results. While grab sampling techniques are required to produce real-time results, grid sampling can be achieved by either grab or passive techniques. The exact number of soil gas points required to complete an investigation generally depends on the sampling scheme (e.g., grid system vs. real-time selection) and on the degree of plume resolution which is required.

Several preliminary soil gas samples should be collected and analyzed onsite, if possible, near an area of known contamination. This type of feasibility test is designed to assess whether the compounds of interest can be detected, to evaluate the success of sampling activities (e.g., probe driving and soil gas pumping), and to select an optimal sampling depth.

The usefulness of soil gas sampling in mapping regional contamination is diminished in the immediate vicinity of contaminant sources (e.g., surface spills, tank leaks) because lateral, as well as vertical, concentration gradients are established. As a result, the remote detection of overall groundwater contamination plumes can be distorted near surface sources. Soil gas samples collected near a subsurface source often show anomalously high VOC concentrations compared to VOC concentrations in the underlying groundwater. Soil gas probes should not be sampled less than 50 feet apart because the resolution of most soil gas techniques is exceeded at such close intervals. Differences in VOC concentrations among closely spaced soil gas probes is as likely to result from small-scale heterogeneities in the soil as from significant changes in the parameter of interest (e.g., groundwater contamination).

The results from grab sampling techniques are generally more depth-dependent than those from passive techniques because the former represent an instantaneous picture of the vadose zone rather than an integrated measurement over time. In addition, pumping techniques associated with grab sampling can locally disrupt VOC gradients in shallow soil gas. Selection of a sampling depth is primarily related to (i) the volatility of the VOC, (ii) the proximity to soil or groundwater contamination, and (iii) the biodegradability of VOC's. Compounds which are both resistant to degradation and volatile (e.g., chlorinated solvents) can be detected in soil gas under most environmental conditions. Conversely, compounds which have low diffusion coefficients (volatility) or are subject to degradation in shallow soils often must be sampled closer to the contaminated soil or groundwater.

Biodegradation of VOC's can produce a variety of by-products depending on the substrate (parent compound) and on subsurface redox conditions. For example, the reductive dehalogenation of chlorinated solvents such as TCE and PCE produce more volatile compounds (e.g., DCA and DCE isomers) which can be detected in soil gas. By contrast, petroleum hydrocarbons are often oxidized to form water-soluble (and relatively non-volatile) metabolites such as alcohols, phenols, organic acids and aldehydes. Ultimately, organic compounds are degraded to form ubiquitous soil gases such as carbon dioxide or methane.

12.2.4 Analytical Methodologies

The analytical instrumentation used in a soil gas investigation depends on the objective of the study, time and cost constraints, and the method of field sampling. Analytical instruments can generally be classified as follows: field monitors, field gas chromatographs, vehicle-mounted gas chromatographs, and chemical laboratories.

The simplest instruments are portable vapor meters (field monitors) which are equipped with a flame ionization detector (FID) or photoionization detector (PID). Instruments such as the organic vapor meter (OVM), organic vapor analyzer (OVA), HNU and Photovac TIP are designed to provide an estimate of total organic vapor concentrations in soil gas samples. A major drawback to the use of these instruments, for any purpose except gross screening, is that they cannot provide compound identification. Moreover, these instruments generally have markedly different response factors to VOC's depending on the physical properties and chemistry of contaminants. While these field meters are portable and easy to operate, the soil gas data which they produce is generally difficult to interpret.

Portable gas chromatographs such as the Photovac 10S and Thermo Electron 511 have a distinct advantage over the field monitors in that individual compounds can be identified and a number of different detectors can be utilized. The primary limitations to portable GC's include a lack of temperature programming, a limited number of available columns and detectors, and a tendency to be significantly affected by changes in ambient conditions.

Mobile laboratories or vehicle-mounted GC's provide the greatest versatility for field analytical work; however, mobile labs are quite expensive and require support equipment and an analytical chemist. A mobile soil gas laboratory is operated out of the WCC office in Santa Ana; however, the majority of these units are available through specialized subcontractors.

Chemical laboratories are probably the most reliable alternative for the analysis of passive samplers since these samplers cannot provide real-time results anyway. Moreover, the wet chemistry (solvent desorption) required for passive samplers is difficult to perform in moderately-sized mobile labs. Chemical laboratories are a less desirable alternative for analyzing grab samples due to the difficulties in storing, transporting and preserving gas samples. Grab samples which must be analyzed in a laboratory should be collected on adsorbents (e.g., pumped through charcoal tubes) rather than collected in "gas-tight" containers (e.g., glass cylinders, Tedlar bags or stainless steel bombs).

12.2.5 Applicability to Hazardous Waste Sites

Soil gas sampling techniques (both passive and grab) have been used to assist in the following hazardous waste activities:

- o locating source areas for buried VOC's in landfills;
- o monitoring the migration of methane and other landfill gases;
- o delineating and differentiating groundwater plumes in industrial areas containing multiple contributors;
- o monitoring in-situ remediation techniques such as biodegradation and vapor extraction;
- o locating leaks in subsurface tanks and pipelines; and
- o estimating the migration of injected wastes containing VOC's.

12.2.6 Data Analysis and Evaluation

Soil gas sampling is considered a remote detection technique insofar as it provides an indication of the parameter of interest (e.g., groundwater or soil contamination). Therefore, interpretation of soil gas data is as important as the collection and analyses of field samples. There are a variety of factors which should be considered when interpreting soil gas data. Some of these factors include the following:

- o depth to groundwater or soil contamination;
- o potential barriers to gaseous diffusion in the vadose zone (e.g., clay lenses or perched water);
- o proximity of soil gas sampling points to underground utilities;
- o proximity of soil gas sampling points to subsurface sources (e.g., underground tanks, leaks, surface spills);
- o presence of asphalt or concrete pavement overlying the sampling point;

- o volatility, phase partitioning, and other physical properties of the VOC's;
- o potential chemical and/or biological degradation of VOC's;
- o depth of soil gas probes or passive samplers;
- o concentrations of VOC's in the above-ground air (atmosphere); and
- o episodic factors which may have occurred either during or prior to sampling (e.g., rainfall, freeze, temperature or barometric pressure fluctuations).

Soil gas results should be interpreted on a semi-quantitative basis and only related to actual VOC concentrations in groundwater or soil when site-specific correlations can be calculated. Linear regression analysis of a log-log plot of soil gas vs. groundwater concentrations can be performed to assess the relationship between the two parameters. Even for correlations where "r" exceeds 0.95, predictions of VOC concentrations in groundwater (based on soil gas results) should be interpreted on an order-of-magnitude basis. Generally, higher correlation coefficients are calculated for deep aquifers than for shallow groundwater. The difference between shallow and deep contamination is related to the steepness of the chemical concentration gradient in soil gas.

Concentration contouring of soil gas data on site maps is acceptable if it is done on an order-of-magnitude basis and it is understood that soil gas contours may differ from the shape of the underlying groundwater plumes; particularly near the edges of the plume. The air/water partitioning, gaseous diffusion, and analytical detection limits for VOC's will influence the resolution with which soil gas sampling defines the distribution of any particular compound in groundwater or soil. Generally, there are very few universal constants which describe the relationship between soil gas results and subsurface contamination. Interpretation of soil gas data should be completed on a qualitative or semi-quantitative basis in most instances.

Soil-gas investigation should be interpreted with particular caution under the following conditions:

- o confined aquifers or regions containing extensive perched water zones;
- o extremely wet soil conditions (air-filled porosity of soils should be at least 5 percent);
- o sites where there are many surface spills or sources of VOC's in the shallow soil (e.g., tank farms, refineries, bulk storage and transfer terminals);

- trace concentrations (<10 ppb) of VOC's in groundwater at depths greater than about 50 feet;

- soils in which petroleum hydrocarbons, carbonyl compounds, or other readily oxidized VOC's can be quickly degraded; and

- semi-volatile products or compounds (e.g., PCB's or waste oils) unless samples are analyzed for gaseous degradation by-products rather than product constituents.

12.3 Headspace Sampling

12.3.1 Collection Methods

Headspace sampling can be performed using any of the instruments recommended for soil gas sampling. As a matter of practice, the field monitoring instruments are most often used because headspace analysis of soil samples is primarily a screening procedure. Generally, field instruments, equipped with either a PID or FID, are used to screen the soil samples. Sample collection and headspace analysis methods for soil are outlined below:

(1) Collect soil sample using split-spoon sampler, hand auger or other apparatus which will yield a soil core or intact sample.

(2) Transfer approximately 100 to 200 cubic centimeters of sample to a sealable plastic bag or other closed container into which a vapor probe can be inserted.

(3) Agitate the sample in the bag or container in order to break up the soil matrix and maximize the surface area of soil which is in contact with the headspace.

(4) Insert the instrument probe or syringe (if GC analyses are performed) inside the bag or container, sealing around the opening as much as possible.

(5) Read the concentration of organic vapors after a pre-determined equilibration period has elapsed (at least 30 seconds) or after the instrument read-out has stabilized.

(6) Record the organic vapor concentration and the gross physical characteristics of the sample (e.g., dry, wet, sandy, clayey, discolored).

12.3.2 Applications of Headspace Analyses

The most common application of soil headspace analysis is screening soil samples which are collected during drilling, excavating, or trenching operations. Assuming that a correlation between VOC concentrations in headspace and laboratory analyses can be established, the number of soil samples which must be submitted to commercial laboratories may be reduced significantly.

Headspace analyses are useful in that they can provide real-time data for soil removal operations, where decisions regarding the extent of soil excavation and its disposal must be determined on-site. In addition, headspace analyses of soils encountered during geotechnical investigations and other non-hazardous waste projects can be screened for health and safety purposes.

12.3.3 Data Interpretation

The most obvious factor which will affect OVM or OVA readings is the type of detector which is used (e.g. FID vs. PID). Generally, the FID will be most appropriate for aliphatic hydrocarbons and certain oxygenated solvents while the PID will be more sensitive to aromatic and halogenated hydrocarbons. PID lamps of different ionization energies will respond with varying degrees of sensitivity to the same gases, and are significantly affected by high humidity. Generally, the FID response is proportional to the number of carbon-hydrogen bonds and, therefore, can be used to estimate concentrations of total hydrocarbons.

Physical characteristics of the soil (e.g., temperature, grain size, moisture content, organic carbon content) have a significant effect on the correlation between headspace analyses and laboratory results. Specifically, anomalously low headspace readings are often associated with soils which are either wet or contain a high percentage of organic materials. This observation results from the partitioning of VOC's into the organic or aqueous phases associated with soil grains. Conversely, dry coarse-grained soils tend to have minimal VOC adsorption but retain vapors in the air-filled pore spaces. As a soil sample is agitated prior to field analysis, VOC's are released from the soil gas to the headspace and, consequently, headspace readings are anomalously high compared to the concentration of VOC's which are desorbed from soil samples during laboratory analysis.

12.4 Quality Assurance Procedures

Quality assurance procedures should be implemented throughout both the sampling and analytical phases of a soil gas investigation. QA procedures for passive samples consist primarily of burying the adsorbent deep enough in the ground so that it is not affected by atmospheric air. The passive samples are factory-sealed and should not be opened prior to their installation or burial. Similarly, the samplers must be resealed after collection for transport to the laboratory. Normal procedures for solvent blanks, spike recoveries, and chain-of-custody documentation should be followed by the laboratory which analyzes passive samplers.

Grab sampling techniques require that soil gas probes be cleaned with steam or hot water and soap before use. If probes are used more than once between cleanings, they should be checked for contamination by pumping atmospheric air through the probe, injecting the sample into a GC, and comparing the resulting chromatogram to that of atmospheric air. If there are significant differences between the chromatograms, it is likely that the probe contains residual contamination. Steel probes, adaptors, and/or sampling ports should be utilized to minimize the possibility of cross-contamination. A sufficient number of interchangeable sampling components should be available so that decontamination does not need to be performed in the field.

If soil gas samples are drawn and sampled through soft tubing, system blanks should be run after each soil gas sample is withdrawn to check for residual contamination. Similarly, syringes, reducers, and any other reusable sampling parts should be checked periodically for contamination. Teflon tubing should never be used for sampling VOC's. Soil gas investigations should be conducted so that less contaminated areas are sampled before more contaminated ones.

A vacuum gauge or flow meter should be installed on the air pump to assess whether a representative soil gas sample is withdrawn from the subsurface. Generally, if the vacuum pressure exceeds 12 inches of mercury, the soil is either water-saturated or does not have a sufficient air-filled porosity to yield a sample. If soil gas samples are collected from the exhaust side of a vacuum pump, tests should be conducted to confirm that atmospheric air is not drawn into the gas stream at high vacuum levels and to document that pump components are not a source of contamination.

It is recommended that cylinders, bags, cannisters, and other containers designed for the storage and transport of gases not be used in soil gas investigations. It has been the experience of the author that reproducible results are difficult to obtain when using gas containers. The loss of VOC's during storage and transport varies significantly with environmental conditions, vapor pressure of contaminants and sorptive properties of the container walls.

Field monitoring instruments (e.g., OVA, OVM, HNU) should be calibrated with a gas standard as is outlined in WCC Health and Safety Manual. The standard should be run several times during the course of a day to check for possible changes in detector response which may require recalibration. The field monitors should be calibrated with the VOC of interest, assuming the standard is available and its use is within health and safety guidelines.

Field gas chromatographs such as the Photovac 10S and Thermo Electron 511 require repeated calibration with analytical standards prepared in gas, methanol or water. Due to a lack of temperature controls on the field

GC's, retention times and detector sensitivity for individual compounds tend to vary significantly with time. Field GC's equipped with computing integrators are preferable to those which use strip-chart recorders because integrators can be programmed for compound identification and generally yield more accurate results under difficult chromatographic conditions. A standard injection (i.e., external standardization) should be made after every three to five sample injections. Additionally, compound identification should be performed on more than one column in order to circumvent the problems associated with coelution (misidentification) of closely related compounds. If the field GC is used for fuel fingerprinting (i.e., the comparison of soil gas chromatograms to those of known products), the frequency of external standardization may be reduced. However, it should be noted that aging processes (e.g., volatilization, degradation) as well as changes in chromatographic conditions can complicate fuel identificaton which is based solely on soil gas fingerprints.

Laboratory GC's mounted in field vehicles (mobile laboratories) should be subject to quality assurance procedures similar to those described for field GC's. In addition, many of the quality control procedures outlined for analytical laboratories in this and other technical memoranda may be applied to the mobile units.

LIST OF REFERENCES

Barsky, J.B., S.S. Que Hee and C.S. Clark, American Industrial Hygiene Association Journal, (46), p. 9, 1985.

Callender, A.B. and A. Bohrnerud, Proceedings of the Woodward-Clyde Consultants Professional Development Central Symposium, St. Louis, Missouri, 1986.

Hutzler, N.J., L.T. Londo and T.C. Crittenden, Proceedings of the ASCE Conference, Minneapolis, Minnesota, p. 720, American Association of Civil Engineers, 1982.

Jury, W.A., W.F. Spencer and W.J. Farmer, Journal of Environmental Quality (12), p. 558, 1983.

Kerfoot, H.B. and C.L. Mayer, Ground Water Monitoring Review (6), p. 74, 1986.

MacKay, D. and W.Y. Shiu, Journal of Physical Chemistry Reference Data (10), p. 1175, 1981.

Marrin, D.L., Proceedings of the 1985 Hazardous Materials Management Conference West, Long Beach, California, p. 112, Tower Conference Management Company, 1985.

Marrin, D.L. and H.B. Kerfoot, Environmental Science & Technology (21), in press, 1987.

Marrin, D.L. and G.M. Thompson, Journal of Ground Water (25), p. 21, 1987.

Spittler, T.M., L. Fitch and S. Clifford, Proceedings of the Symposium on Characterization and Monitoring of the Vadose Zone, Las Vegas, Nevada, p. 134, National Water Well Association, 1985.

Swallow, J.A. and P.M. Gschwend, Proceedings of the 3rd National Symposium on Aquifer Restoration and Groundwater Monitoring, Columbus, Ohio, p. 327, National Water Well Association, 1983.

Thompson, G.M. and D.L. Marrin, Ground Water Monitoring Review (7), 88, 1987.

Vorhees, K.J., J.C. Hickey and R.W. Klusman, Analytical Chemistry (56), p. 2604, 1984.

FIGURE 12-1

RELATIONSHIP BETWEEN CALCULATED HENRY'S LAW CONSTANTS AND MEASURED GAS-LIQUID PARTITIONING COEFFICIENTS

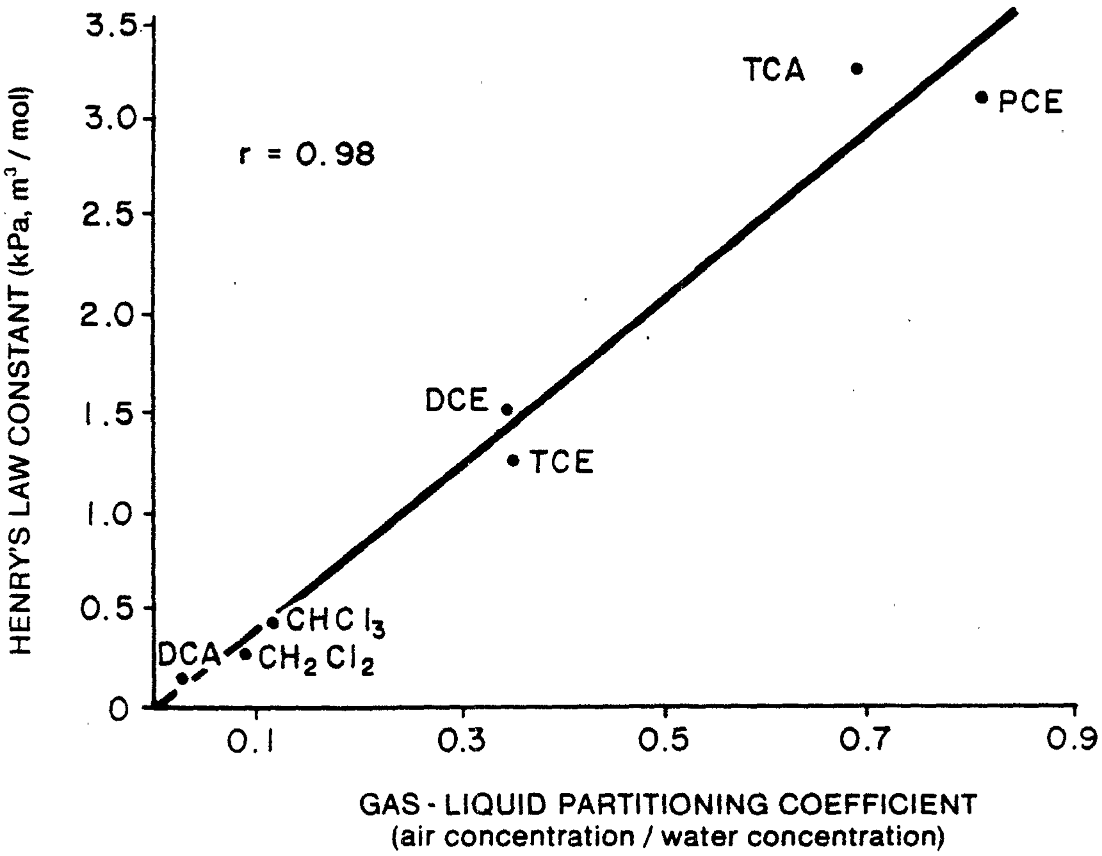


FIGURE 12-2

HENRY'S LAW CONSTANTS AND APPROXIMATE VAPOR PRESSURES FOR SOME COMMON ORGANIC CHEMICALS AT 25°C

Compound	Approximate Vapor Pressure	Henry's Law Constant
iso-Octane	40	330
Methylcylohexane	40	40
Benzene	80	0.6
Naphthalene	0.05	0.04
Anthracene	0.04	30
1,1-Dichloroethene (DCE)	500	15
1,1,1-Trichloroethane (TCA)	100	3
1,2-Dibromoethane (EDB)	2	0.1
Arochlor 1254 (PCB)	0.007	>0.001
2-Butanone (MEK)	80	0.02

NOTE: Vapor pressures and Henry's Law Constants are presented in the units of mm Hg and kPa m^3/mol, respectively.

FIGURE 12-3

VERTICAL PROFILE OF HALOCARBON CONCENTRATIONS IN SOIL GAS OVERLYING A CONTAMINATED AQUIFER. F-11, CH_2Cl_2 AND TCA APPEAR TO HAVE AN ATMOSPHERIC OR VADOSE ZONE SOURCE RATHER THAN A GROUNDWATER SOURCE.

		F-11	CH_2Cl_2	CCl_3H	TCA	CCl_4	TCE	PCE
AIR ABOVE GROUND[a]		0.004	0.005	-	0.01	0.01	-	0.001
SOIL MATERIAL	SOIL GAS							
	10 ft	0.007	1	0.007	0.02	0.008	0.006	0.01
SILT, SAND GRAVEL	25 ft	0.006	0.2	0.009	0.01	0.009	0.02	0.04
	50 ft	0.005	0.1	0.03	0.001	0.09	0.03	1
CLAY								
SAND SILT CLAY	90 ft	0.004	0.08	0.3	0.001	2	9	5
WATER TABLE SURFACE[b]	100 ft	0.003	2	1	-	0.1	142	0.05
CARRANZA WELL	100 - 106 ft	0.009	6	1	0.1	0.2	558	0.2

[a] Concentrations expressed in μg/L gas ± 20% (one standard deviation).

[b] Concentrations expressed in μg/L water ± 20%.

FIGURE 12-4

PASSIVE SAMPLER AND MANIFOLD ASSEMBLY
(TAKEN FROM KERFOOT & MAYER, 1986)

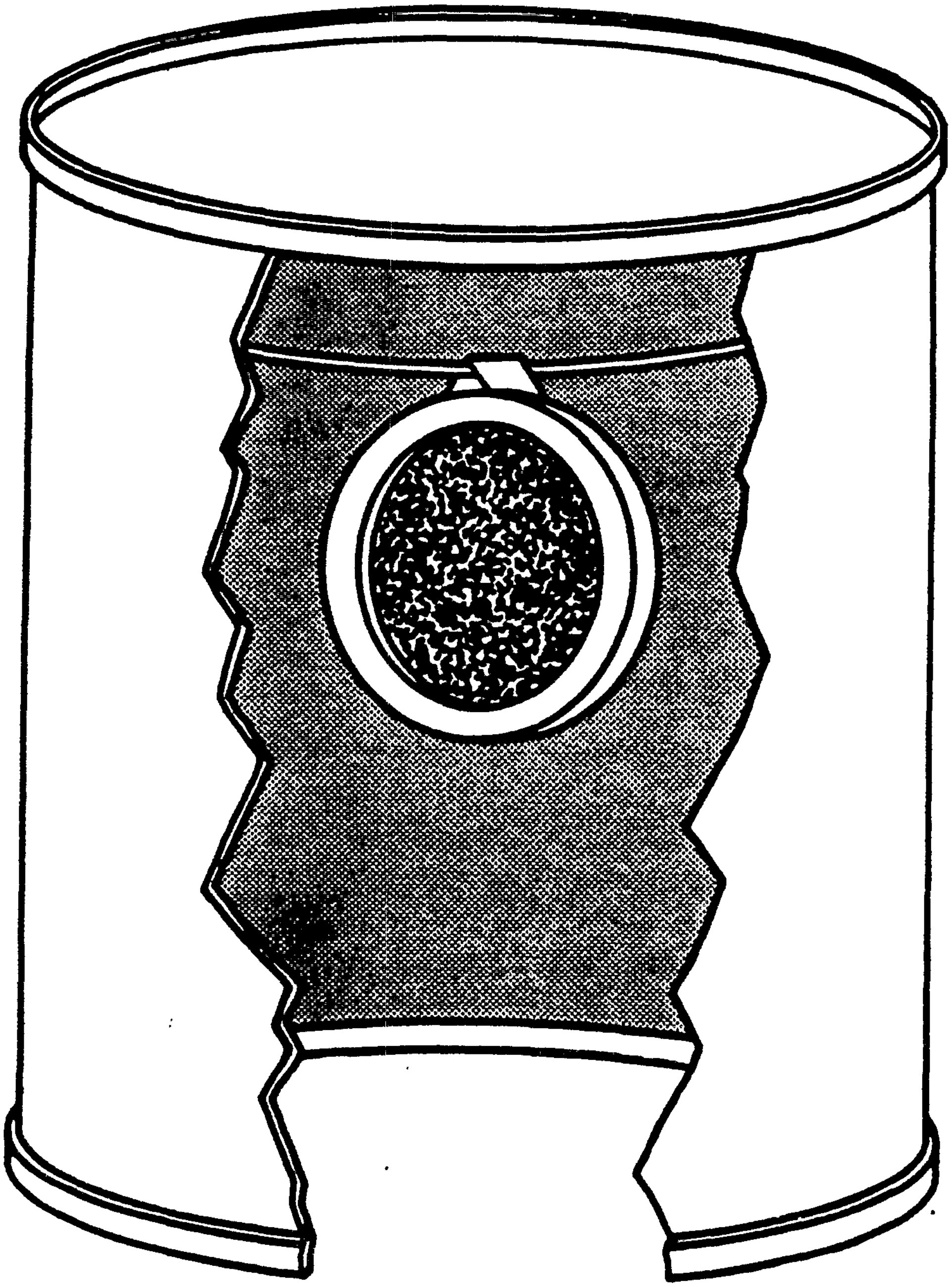


FIGURE 12-5

SOIL GAS SAMPLING PROBE AND ADAPTOR
(TAKEN FROM MARRIN & THOMPSON, 1987)

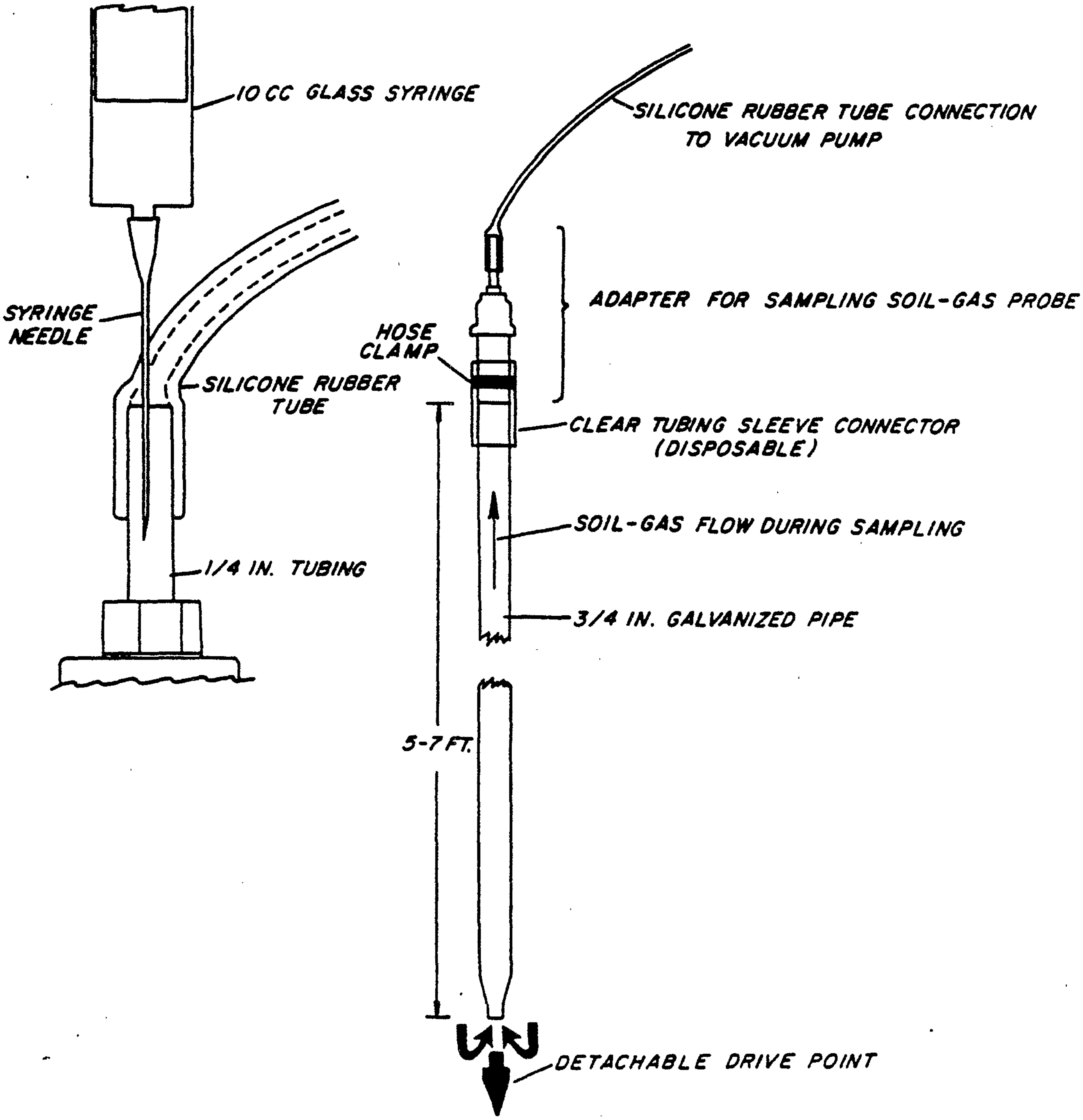
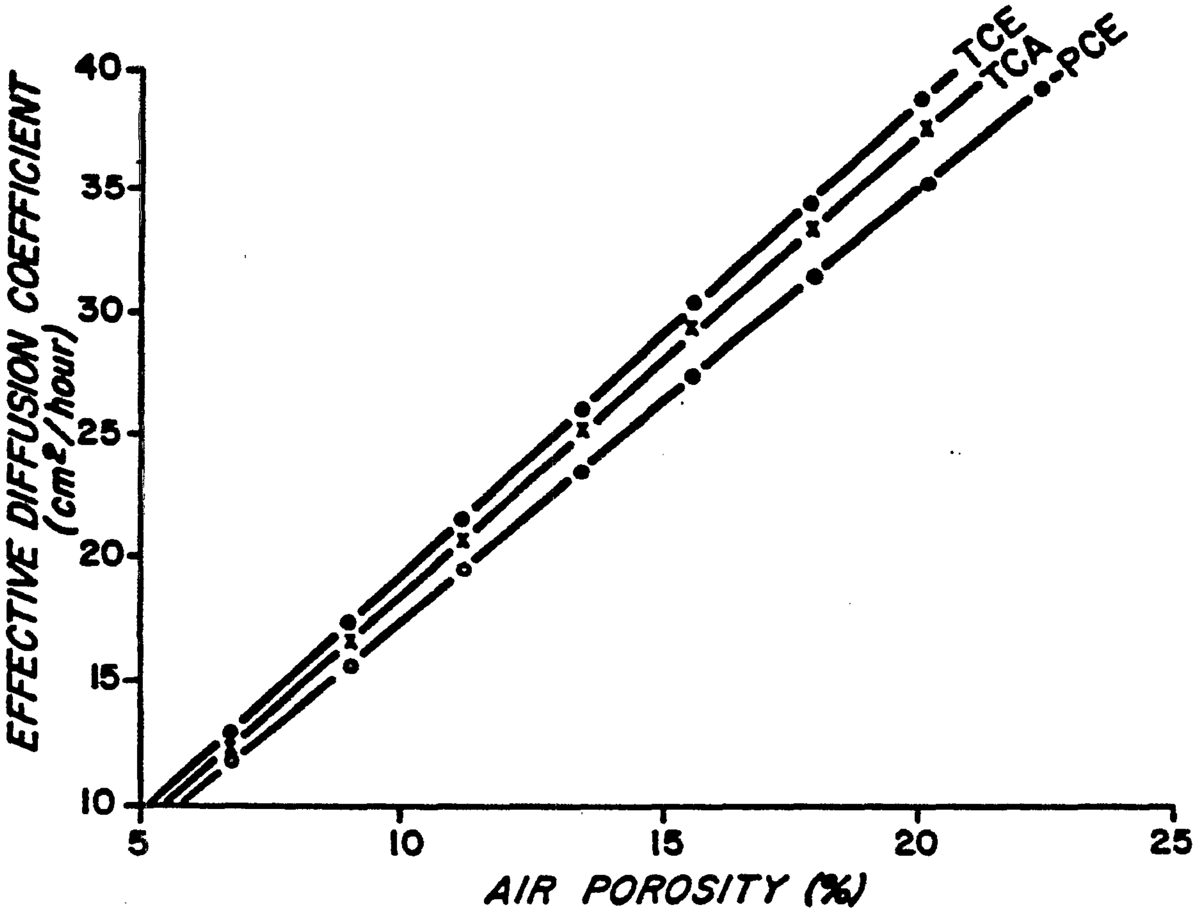


FIGURE 12-6

RELATIONSHIP BETWEEN AIR-FILLED POROSITY OF THE SOIL AND THE EFFECTIVE DIFFUSION OF VOC'S



Attachment B
Health and Safety Plan
(HASP)

Woodward-Clyde Consultants

HEALTH AND SAFETY PLAN

DU PONT NEWPORT LANDFILL

PROJECT:	87C2665
NAME:	Du Pont Newport Landfil Newport, Delaware
PROJECT MANAGER:	Alfred M. Hirsch, Ph.D.

1.0 INTRODUCTION

This Health and Safety Plan establishes guidelines and requirements for the safety of Woodward-Clyde Consultants' (WCC) field and laboratory personnel while conducting field and laboratory activities associated with field work described from herein. All employees of WCC are required to read the plan, sign the attached Compliance Agreement, and abide by the provisions herein.

The Health and Safety Plan is based on a review of available data and an evaluation of the potential hazards associated with the referenced project. This plan outlines the health and safety procedures and equipment for activities at this site in order to minimize the potential for exposure of field personnel to potentially contaminated materials.

2.0 BACKGROUND

Du Pont's Newport Plant is a pigment manufacturing plant located at James and Water Streets in Newport, Delaware. The site was originally owned and operated (from 1902 to 1929) by Henrik J. Krebs for the manufacture of Lithopone, a white inorganic pigment. In 1929, Du Pont purchased the site, which has since been used to manufacture Lithopone and other materials, including organic and inorganic pigments.

During plant operations, areas of the site bordering the Christina RIver were landfilled as a means of waste disposal. Landfiling of wastes may have occurred between 1902 and 1074, when Du Pont terminated such on-site landfill activities. Landfilling occurred in two areas designated the "south disposal site" and the "north disposal site". The south disposal site is an approximately 15 acres landfill located across the Christina River from the plant, operated from approximately 1902 - 1953. Materials deposited in this landfill consisted of primarily insoluble residues of zinc and barites ores, which were pumped through a pipeline under the Christina River. Some dikes and berms were constructed to contain the material. This material hardened to a sandstone consistency, according to Du Pont's records. In 1973, the State of Delaware, Department of Highways, deposited approximately 130,000 cubic yards of soil from highway construction at this location, covering the south disposal site with several feet of soil.

The north disposal site (see Figure 2-1) was used for disposal of general refuse and process wastes from the early 1900's until 1974. The north disposal site covers approximately 7 acres, and received approximately 25,000 tons of material. Additional details concerning wastes disposed in the north disposal site are presented in Section 3. The fill depth ranges from about 13 feet at the southwestern edge to 8 feet in the northwestern portion. The north disposal site was operated under a State of Delaware permit from 1968 until its closure on January 1, 1975. Upon closure, this site was capped with 2 feet of clay.

After closure of the north disposal site, groundwater monitoring was begun in 1976. Twelve monitoring wells are currently in operation. Water quality data has been collected from these wells on a quarterly basis and submitted to the Delaware Department of Natural Resources and Environmental Control.

In 1984, Du Pont sold the pigments operation at the Newport Plant to Ciba-Geigy, which currently operates the eastern portion of the plant. Du Pont continues to operate a chromium dioxide magnetic tape manufacturing plant on the western portion of the plant site. Du Pont has retained ownership of the north and south disposal sites.

In 1986, the Mitre Corporation, under contract to the U.S. EPA, conducted a site evaluation and Hazard Ranking System (HRS) scoring of the north disposal site, in accordance with provisions of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or "Superfund"). An overall HRS score for the site of 51.91 was developed, based upon observed groundwater contamination and the potential (not observed) impact on regional water supply wells. Surface water and airborne exposure routes were considered insignificant in the HRS scoring. Based upon the HRS score, the U.S. EPA has proposed inclusion of the site on the Superfund National Priority List (NPL), which would require remedial investigations, feasibility studies, and possible remedial actions under the terms of CERCLA. EPA's decision to include the site on the NPL appears to be based entirely upon the HRS score, which is a preliminary screening tool. No consideration was given to additional data available for the site including available groundwater monitoring data, or to an evaluation of the actual risk posed by the site. The subsequent sections of this report describe additional available information, in terms of better defining the actual and potential risks associated with the north disposal site.

3.0 STAFF ORGANIZATION, QUALIFICATIONS AND EXPERIENCE

Health and safety responsibility lies in a chain of command headed by the Project Manager, maintained in the field by the Site Safety Officer, continuing to all field personnel. Consultation on health and safety issues, and internal review and approval of plans is provided by a Corporate Health and Safety Officer and the Business Unit Health and Safety Officer.

The responsibilities and authority of the Project Manager, Site Safety Officer, Business Unit Health and Safety Officer and Corporate Health and Safety Officer are described below.

3.1 PROJECT MANAGER

The Project Manager (PM), Dr. Alfred M. Hirsch, Ph.D., will be responsible for the overall implementation and monitoring of the health and safety program by:

- Providing adequate resources to conduct the site investigation.
- Ensuring appropriate protective equipment is available and properly used by all personnel, in accordance with the health and safety plan.
- Ensuring personnel health and safety awareness by providing them with proper training and familiarity with health and safety procedures and contingency plans.

- Supervising and monitoring the safety performance of all personnel to ensure their proper work practices are conducted in accordance with the health and safety plan.

- Correcting any work practices or conditions that would expose personnel to possible injury or hazardous conditions.

- Supervising compliance with health and safety requirements and enforcing disciplinary actions when unsafe practices occur.

AUTHORITY

- Determining matters relating to schedule, cost and personnel assignments on hazardous waste management projects that are not safety related.

- Can temporarily suspend field activities, if health and safety of personnel are endangered, pending an evaluation by the HSO and/or CHSO.

- Can temporarily suspend an individual from field activities for infractions on the health and safety plan, pending an evaluation by the HSO, CHSO, and/or CHSA.

3.2 SITE SAFETY OFFICER

The Site Safety Officer (SSO), Mr. James Buczala, is responsible for the daily proper implementation of the site Health and Safety Plan. The SSO reports to the Business Unit Safety Officer (HSO) in matters pertaining to site safety. The SSO is designated for a specific project based on appropriate experience and with the approval of the HSO.

The SSO must have completed Hazardous Waste Basic Health and Safety Training and CPR/First Aid Training. A science degree with additional training in instrumentation, toxicology, industrial hygiene, and related subjects is desirable.

The amount of relevant experience will depend on the hazards expected at the site. Over two years hazardous waste experience is recommended for B level sites and over one year for C level sites. The individual must have shown a conscientious and positive attitude towards health and safety during past site work to be considered for an SSO.

The responsibilities of the SSO are:

1. Enforce compliance with the site safety plan.

2. Conduct on-site safety briefings for all site personnel.

3. Manage health and safety equipment (respirators, instruments, boots, gloves, suits) used at the site.

4. Perform air-monitoring as specified in the site safety plan.

5. Establish work/rest regimen in conjunction with site manager.

6. Emergency response provisions in conjunction with local authorities (hospital, fire, police).

7. Continuously monitor health and safety conditions during the site work.

8. Maintain a site safety log to record air monitoring results, weather conditions, employees on-site, safety problems, and similar information.

9. Report all incidents to the HSO.

10. Provide a post-site work review to the HSO regarding safety.

AUTHORITY

The SSO shall have the authority to stop work if conditions are deemed unsafe. The SSO also has authority to temporarily remove an individual from the site if he/she is not complying with the safety plan. In both cases, the SSO will promptly confer with the HSO regarding follow-up actions.

3.3 BUSINESS UNIT HEALTH AND SAFETY OFFICERS (HSO):

RESPONSIBILITIES

- Interface with project managers as may be required in matters of health and safety.
- Report to CHSO on health and safety matters.
- Develop or review and approve appropriate health and safety plans for hazardous waste management projects and submit to the CHSO for approval.
- Appoint or approve site safety officers to assist in implementing the health and safety plan.
- Monitor compliance with approved health and safety plans.
- Assist project managers in seeing that proper health and safety equipment is available for projects in the business unit.
- Approve personnel to work on hazardous waste management projects with regard to medical examinations and health and safety training.

AUTHORITY

- Can suspend work or otherwise limit exposures to personnel, if a health and safety plan appears to be unsuitable or inadequate.

- Can direct personnel to change work practices, if they are deemed to be hazardous to health and safety of personnel.

- Can remove personnel from projects, if their actions or condition endangers their health and safety or the health and safety of co-workers.

3.4 CORPORATE HEALTH AND SAFETY OFFICER (CHSO):

RESPONSIBILITIES

- Direct the implementation of the health and safety program of the operating group and provide recommendations for improvement of the program.

- Coordinate health and safety activities of the business unit offices in the operating group.

- Review and approve health and safety plans.

- Investigate reports of incidents or accidents and report accidents or incidents to the CHSA and EVPP.

- Assist CHSA in implementing training for employees in the operating group.

- Provide industrial hygiene/chemical safety guidance to CHSO and HSO.

o Audit key aspects of health and safety program.

AUTHORITY

o Approve the qualifications of employees to work at hazardous waste sites.

o Approve project health and safety plans.

4.0 HAZARD ASSESSMENT

A variety of inorganic and organic waste materials were disposed in the north disposal site from approximately 1902 to 1974. This section summarizes available information concerning wastes quantities and characteristics, including an identification of potential hazardous constituents. The primary sources of this information are the following documents:

o "Notes on Lithopone" - C.K. Cooper, 8 August 1979.

o Memorandum - P.E. Kress to J.C. Deming, 6 November 1979.

o Letter - M. Barszcz (Du Pont) to R. Gordon (U.S. EPA) titled Newport Waste Disposal Operations, 22 July 1980.

o Memorandum titled "Waste Disposal Survey" - R.E. Kress to P.F. Brown - 29 October 1980.

o Letter - R.J. Mattson (Du Pont) to S.R. Wassersug (U.S. EPA) 21 May 1986.

The north disposal site comprises about 7 acres immediately north of the Christina River. This site received a variety of waste materials during its operations between 1902 - 1975. Table 4-1 presents a summary of materials known or suspected to have been disposed in the north disposal site. No known disposal of RCRA - listed hazardous wastes has occurred at the north disposal site. The major waste materials containing potentially hazardous constituents, based upon available information, are discussed below.

Lithopone Wastes

The lithopone process produced a white pigment composed of barium sulfide and zinc sulfate. Some lithopone pigments (off-quality) and lithopone wastes may have been disposed in the north disposal site. Several thousand tons of fill dirt containing zinc and barites ore were also placed in the north disposal site.

Wastes from the Lithopone process consisted of insoluble ore residues. Zinc ore was treated with sulfuric acid to dissolve zinc. Insoluble residues were precipitated with ferric hydroxide, resulting in a "red mud" which was disposed. The zinc process also produced a by-product filter cake which was sold for cadmium recovery.

The barium sulfate ore was roasted in kilns to reduce the sulfate to barium sulfide, which was dissolved in hot water. The insoluble ore residues formed a "black mud", which was disposed. The waste muds were generated in an estimated ratio of 1 part red mud to 3 parts black mud. Best estimates indicate disposal of approximately 25,000 tons of this mixture over approximately 15 acres in the south disposal site. After 1953, any remaining ore residue wastes were disposed in the north disposal site. According to the available records, after disposal, the muds solidified to a "sandstone consistency". Potential contaminants from lithopone wastes and ore residues include barium, zinc, and cadmium.

Copper Phthalocyanine Wastes

Copper phthalocyanine, a stable blue-green pigment has been manufactured at the plant since 1947. In general, by-products have been discharged to municipal waste treatment facilities. Some off-quality pigments were disposed at the north disposal site. According to data provided by Du Pont, copper phthalocyanine is essentially non-toxic by the oral route. It has been approved by the U.S. Food and Drug Administration (FDA) for use as a pigment in polymers used in food packaging. According to Merck (1983), this compound is also approved by FDA for use in polypropylene sutures.

Quinacridone Wastes

Quinacridone, a stable red organic pigment, has been manufactured at the plant since 1958. By-products of the process have generally been discharged to municipal wastewater treatment facilities, with the exception of an insoluble tarry solid, which was disposed in the north disposal site until 1974. Primary constituents of this tar are biphenyl, diphenyl ether, and alpha-methyl naphthalene. The quinacridone process also used tetrachloroethylene and it is possible that some quinacridone wastes may have become contaminated with tetrachloroethylene or Dowtherm constituents. Off-quality quinacridone pigments were also disposed in the north disposable site. Soluble components of quinacridone wastes, including tetrachloroethylene if present, represent potential groundwater contaminants from this material. According to data supplied by Du Pont, quinacridone itself is essentially non-toxic by the oral route, and has been approved by FDA as a colorant for ply-olefins used in food packaging.

"Afflair" Pigment Wastes

Afflair, a stable white pigment, consists of mica coated with titanium dioxide. Some scrap mica (a natural mineral), was disposed at the north disposal site. This material is unlikely to represent a significant source of contamination.

Metal Production Wastes

From 1950 to 1960, several metals and metal alloys were manufactured at the plant. These included titanium, zirconium, and silicon, which are relatively inert substances. Unknown, small quantities of off-grade materials were disposed in the north disposal site.

For about two years during this period, thoriated nickel (nickel containing 2 - 5 percent of ThO_2) was produced. Approximately 20 tons of process wastes (primarily off-grade thoriated nickel) were disposed in the north disposal site under NRC guidelines. Thorium is a radioactive substance.

Since the metals produced are essentially insoluble in their metallic forms, the only potential groundwater contaminant from the metal wastes is potential radioisotopes (thorium and its daughters).

Chromium Dioxide Wastes

Chromium dioxide has been manufactured at the plant since 1966, some of which is used in production of magnetic recording tape (mylar coated with chromium dioxide). Approximately 10 tons of off-quality chromium dioxide (in drums) and mylar recording tape (in bags) were disposed at the north disposal site. The primary potential groundwater contaminant from this material is the heavy metal, chromium, which has not been found in groundwater in significant concentrations.

Miscellaneous Wastes

As shown on Table 3-1 a variety of other wastes including low volume process wastes, laboratory packs, and garbage were disposed in the north disposal site. A variety of low level contaminants could be present in these materials.

A variety of relatively inert materials, including trash, concrete, steel, rubber refuse, nylon shutters, and corian (imitation marble sheets) were also disposed in the north disposal site. No significant groundwater contamination would be expected from these materials.

Summary

A variety of inorganic and organic waste materials were disposed in the north disposal site. Potential suspected groundwater contaminants which could be identified based upon the waste disposal inventories include:

- o Barium;
- o Cadmium;
- o Chromium;
- o Zinc;
- o Tetrachloroethylene; and
- o Radioisotopes.

Actual groundwater monitoring data for the site is discussed in Section 5.

5.0 MONITORING EQUIPMENT AND ACTION LEVELS

Based upon the information collected by WCC for the report entitled "Evaluation of Existing Conditions at the Newport Plant - North Disposal Site" dated 19 March 1987, the following monitoring equipment will be required during invasive activities performed under this Health and Safety Plan.

A) Organic vapor monitoring equipment - HNu Photoionization Detector with a 10.2 eV or an 11.7 eV lamp, or an Aids Model 580 Organic Vapor Meter

B) Combustible Gas Meter - MSA Model 260

C) Radiation Survey Meter - capable of evaluating both beta and gamma radiation sources

Based upon a review of the referenced data the following action levels have been established:

A) Organic Vapors 0 - 5 ppm Level D*

5 - 25 ppm Level C*

25 ppm Level B*

* Personnel Protective Equipment required for each level is detailed in Section ___.

B) Combustible Gas - levels 20 percent LEL (methane) - stop work and allow methane to vent off or implement procedures for gas control (addition of slurry to borehole).

C) Radiation - < 0.08 mR/hr - ~~stop~~ continue work ~~until allowed to resume following consultation with a CHSO and a health physicist~~.

0.08 mR/hr to 0.30 mR/hr

~~In addition,~~ all workers shall wear a radiation dosimeter ~~for all on-site work.~~

$>$ 0.30 mR/hr stop work, call CHSO

D) Particulates - the SSO shall determine if particulate concentrations from the field investigation require upgrade to Level C. Visible dust in the breathing zone will require respirator use.

6.0 WORK DESCRIPTION

6.1 TASK 1 - CLUSTER MONITORING WELL INSTALLATIONS

A total of seven monitor well clusters will be installed at the approximate locations shown in Figure A-2. WCC's understanding is that all drilling locations (Task 1 and Task 2) and existing monitoring well locations will be accessible to truck mounted drilling rigs and support vehicles.

6.1.1 TEST BORINGS

At each cluster location an initial test boring of nominal 4-inch diameter will be drilled before the monitoring wells are installed. The test borings will be drilled using a mud rotary rig with split-spoon sampling capabilities. Potable water obtained by the driller from a hydrant at the plant will be used in making up the Du Pont approved bentonite mud drilling fluid. Using a 2-foot split-spoon sampler, soil (overburden) samples will be collected at 5-foot intervals from ground surface to the total depth of the test boring. The samples will be sealed in proper containers for analysis and shipped to ETC (under contract to Du Pont). The samples will be analyzed for heavy metals and volatile organic chemicals.

At the North Disposal Area, the three test borings will be cored with a 2-inch diameter NX bit five feet into the top of bedrock. these cores will be laboratory tested for radioactivity.

6.1.2 DOWNHOLE GEOPHYSICS

All seven test borings will be geophysically logged immediately upon completion of each test hole using WCC downhole geophysical logging equipment and an experienced operator.

6.1.3 MONITORING WELLS

Following the sampling and geophysical logging of each test boring, the individual monitoring wells will be drilled at each cluster location. Except for the differences in screen settings and total depths the anticipated shallow, intermediate and deep monitoring wells will all be installed and developed in a similar fashion.

Utilizing either mud rotary or hollow stem augering techniques, a nominal 8-inch diameter borehole will be drilled to the well's total depth; then the 4-inch stainless steel screen with 4-inch carbon steel casing (riser pipe) will be lowered into the borehole. The selected gravel pack material will be introduced into the annulus outside the screen and brought up to approximately two foot above the top of the screen. Following the positioning of two feet of bentonite pellets (or equivalent) to seal the top of the gravel pack, the remainder of the annular space will be grouted to ground surface with cement grout or 5 percent bentonite cement grout mixture. The top of all the 4-inch steel casings will extend above ground surface approximately two feet, serve as protective casings, and be covered with a cap and matching keyed locks.

The development method will focus on the use of mechanical surging techniques combined with bailing and/or pumping, especially in the lower yielding wells completed in relatively fine-grained sediments. Unless higher yielding zones are encountered, air lifting techniques are expected to be of limited application at this site. The top of casing and ground surface will be surveyed for all newly constructed monitoring wells.

6.1.4 AQUIFER TESTING AND CONTINUOUS MONITORING

Two aquifer tests will be performed to determine the groundwater transmitting and storage characteristics of the Lower Potomac hydrostratigraphic unit (aquifer). Based on the proposed monitoring well construction, 10 feet of 4-inch screen, and available aquifer data, the projected maximum sustainable pumping rate is 15 to 25 gallons per minute (gpm). As a alternative to performing two 72-hour tests, WCC recommends consideration of performing six (6) eight-hour tests.

6.2 TASK 2 - GEOPHYSICAL SURVEYS, SOIL GAS SURVEY, AND SHALLOW PERIMETER WELLS

6.2.1 GEOPHYSICAL SURVEYS

To gain a further understanding of the stratigraphic profile of each disposal site, WCC will undertake resistivity soundings utilizing a Schlumberger configuration along traverses over each disposal area oriented perpendicular to the northwest bank of the Christina River. Three traverse lines will be performed in the North Disposal Area and five in the South Disposal Area. Each traverse will be parallel and separated by 200 feet from all other traverses in the site involved.

6.2.2 SOIL GAS SURVEY

Work conducted by WCC and others has indicated that volatile organic contamination can be evaluated quickly and efficiently by collecting soil gas samples for analysis using a soil vapor probe. The objective of the soil gas survey at the Newport Site is to attempt to delineate the presence and extent of trichloroethylene (TCE) and tetrachloroethylene (PCE) in the vapor phase throughout the disposal areas. This proposal includes collection and analysis of soil gas samples at approximately 150 to 200 locations, located on a grid pattern with a 100 foot node spacing.

The procedure for collecting the soil-gas samples (Appendix A, Attachment 3) involves the insertion of a suitable precleaned probe, such as steel or copper/polypropylene into the soil at a depth of approximately 3 to 5 feet. A sample of the soil gas is then drawn through perforations at the base of the probe with an oil-less vacuum pump. Samples are then analyzed using a field operable gas chromatograph (GC).

6.2.3 PERIMETER MONITORING WELLS

WCC will install eight shallow ("perimeter") monitoring wells around the perimeter of the South Disposal Area at the approximate locations shown on Figure 3 in the RFP. As with the cluster well locations, our understanding is that all of these perimeter well sites will be accessible to a truck-mounted drilling rig and support vehicles.

6.3 TASK 3 - GROUNDWATER SAMPLING AND ANALYSES

WCC will collect groundwater samples from all newly constructed (estimated 29) monitor wells and the existing (12) active monitoring wells during two separate sampling episodes. These samples will be collected in accordance with WCC's the Site Sampling and Analysis Plan (Appendix A) and the QA/QC Plan (Appendix C) to ensure conformance with U.S. EPA Superfund RI/FS guidelines.

The proper sample volumes, treatment, and container usage will be coordinated with ETC (under Du Pont contract), who will perform the necessary laboratory analyses. Groundwater samples will be field analyzed by WCC personnel for pH, and laboratory tested for iron, sulphate as SO_4, and zinc.

6.4 TASK 4 - CHARACTERIZATION OF RADIOACTIVITY

6.4.1 RADIOACTIVITY SURVEY

The North Disposal Area is a seven-acre parcel, in which processed radioactive wastes containing from 2 to 5 percent thoriated nickel (ThO_2), were disposed during a two year period. The distribution of these wastes within the landfill is uncertain. However, Du Pont's records suggest that disposal pits in the landfill are down-river of wells DM-3 and SM-3. Moreover, radioactivity in water samples from two wells at the southwest end of the Site (DM-6 and SM-4) indicate levels slightly above drinking water standards. Therefore, a survey of surface radiation should be carried out to determine whether radioactivity in excess of background levels due to buried thorium waste can be detected.

A survey of surface radiation will be performed using the 100-foot grid system which will be oriented parallel and perpendicular to the Christina River. Moreover, the survey data are to be presented on a map at a scale of 1-inch equals 50-feet. Data points on the traverse lines on the map are to be spaced 25-feet a part.

Prior to commencement of the detailed survey at the North Disposal Area, a reconnaissance survey of radiation will be performed as part of the Health and Safety program for this project. The reconnaissance survey will be carried out using a Ludlum 3 Geiger-Mueller radiation meter.

WCC proposes a detailed radiation survey utilizing a portable gamma ray spectrometer because thorium emits gamma radiation which is detectable using ground radiometric techniques. The spectrometer is capable of measuring thorium activity and is calibrated using a ThO_2 source. Due to the uncertainty of location, the unknown number of possible source concentrations, and the damping effect of soil overburden on detectability of radiation, the entire North Disposal Area will be surveyed at 25 foot intervals along the traverse lines.

6.4.2 GROUNDWATER RADIATION SAMPLING

Available information from the North Disposal Area indicates that radium in water from well SM-4 and gross alpha in well DM-6 are slightly in ex s of drinking water standards. Therefore, additional sample analyses are required to help determine whether the sources are natural materials (i.e., background) or buried waste. It appears unlikely based on the low solubility of thorium, the locations of suspected disposal pits down river from DM-3 and SM-3, and the shallow groundwater conditions that thorium could be transmitted from the disposal pits toward the southwest.

To test this possibility, additional water samples as part of the overall water sampling program will be collected as called for in the RFP from all existing and all new wells within and in the vicinity of the North Disposal Area for analysis of gross Alpha, beta, and gamma radiation.

6.4.3 TEST BORING ROCK CORES

As part of Task 1, NX cores will be obtained in three boreholes in the vicinity of the North Disposal Area. A minimum of 5-feet of bedrock core will be extracted from each boring. The RFP requires that the rock cores be tested in the laboratory to determine levels of alpha, beta, and gamma radiation. The purpose of this analysis is to evaluate background radioactivity from sources in the host rock.

WCC recommends that consideration be given also to collecting several soil samples from the overburden for analysis of alpha, beta, and gamma radioactivity. Studies in New Jersey have shown that Coastal Plain Formations have limited, but significant, sources of uranium and thorium radioisotopes. For this reason, it is possible that the background radiation in the Columbia or Potomac Formations may locally exceed that of the bedrock. Samples could be selected using results from the downhole logging in Task 1. Analysis could be performed by Teledyne Isotopes, for the same unit cost as analysis of rock core samples.

Teledyne has indicated that schedule delays associated with the laboratory analyses to be performed as part of this subtask are not likely. Therefore, WCC is confident that these results may be obtained in a timely manner.

6.5 TASK 5 - CHRISTINA RIVER WATER AND SEDIMENT SAMPLING: TIDAL MEASUREMENTS

6.5.1 RIVER SEDIMENT SAMPLING

Sediment sampling is addressed under a separate Health and Safety Plan.

6.5.2 RIVER WATER SAMPLING

6.5.3 TIDAL AND GROUNDWATER LEVEL MEASUREMENTS

WCC will initiate an hydraulic head monitoring program intended to show any correlations between tidal variation of the Christina River stage and static groundwater levels in monitoring wells at the site. This program will be conducted over a period of about 2 months, beginning at the end of well installation, and it will encompass continuous monitoring of piezometric head levels in existing and newly installed shallow, intermediate, and deep monitoring wells in addition to monitoring river stage in a stilling basin to be installed at the site.

7.0 WORK ZONES AND DECONTAMINATION

At each site Drilling, Exclusion, Support, and Contaminant Reduction Zones (CRZ) will be established prior to the initiation of invasive site activities. These zones will be established for the majority of each invasive site activity, so as to minimize movement of vehicles and personnel around the site. The locations of these areas will also be controlled by current site use.

The Exclusion Zone is the area where contaminants are most likely to be encountered during invasive site activities. Protective equipment is specified for workers in the Exclusion Zone on the basis of location or operation or both in accordance with this HASP.

The CRZ provides an area to minimize the transfer of contaminants from the Exclusion Area to the Support Zone, including personnel and equipment decontamination. The personnel decontamination station will consist of a semi-permanent decontamination line (established for periods of active work at sites) consisting of a segregated equipment drop, detergent washes for boots, gloves, separate detergent wash for cleaner items (hardhats, face shields), a disposable equipment drop, and supplies for washing of hands, faces, respirators, and goggles).

The Support Zone is considered to be free of contamination and includes staging areas, administrative areas, vehicle access routes and parking.

The Exclusion Zone will consist of sub-zones being designated Invasive Work Zones (IWZ). An IWZ includes a 25-foot radius from each boring monitoring well or sampling location. These zones may be designated by cones placed during active work on-site.

7.1 PERSONNEL AND EQUIPMENT DECONTAMINATION

The purpose of decontamination when leaving the exclusion area or other areas with known or suspected contamination is to prevent the transfer of contaminants from the exclusion area to the support area or off-site. Means of contaminant transfer include soil, dust particles, and residual liquids attached to clothing and field equipment.

7.1.1 EQUIPMENT

During sampling and boring activities, augers and any parts of the rig which are encrusted with dirt or mud, or which are suspected of having been splashed with materials at a sampling station, will be washed with high pressure hot water or steam prior to moving to the next borehole location to avoid cross-contamination. This will be performed at the equipment decontamination station in the CRZ.

Equipment: Appropriate parts of drill rigs, vehicles, and other large equipment used in sampling activities will be fully decontaminated prior to leaving the site. Decontamination will consist of a soap and water wash and potable water rinse, or high pressure hot water or steam cleaning as necessary. This will be performed at the equipment decontamination station in the CRZ.

The back and underside of the drilling rig will be protected by plastic sheeting when drilling. This will be done to prevent the rig from becoming contaminated during drilling and spreading contaminants across the surface of the site on the trip back to the CRZ. Potentially contaminated drilling tools will be trucked back to the equipment decontamination station. soil and water sampling equipment (e.g., spoons, trowels, and bailers) will be decontaminated prior to use and will be used immediately or stored in plastic bags or on plastic sheeting.

7.1.2 PERSONNEL

A personnel Decontamination Station will be set up in the CRZ at each drilling location. Before beginning work, personnel will become thoroughly familiar with the following decontamination procedure that will be required when leaving the Exclusion Zone.

At the completion of each day's field operation, at lunch, and if necessary at breaks all disposable clothing and equipment will be discarded in an appropriate waste container (in this case, drums). Contaminated clothing will not be worn into the support area. Contaminated clothing will not be redonned. The drums of disposables as well as decontamination waters will be left in a designated area on-site for future removal.

The personnel decontamination lime will consist of the following stations from the exclusion zone to the support zone:

1. Segregated equipment drop (with wipes for equipment decontamination)
2. Bootie disposal
3. Boot and outer glove wash (Alconox and water)
4. Boot and outer glove rinse
5. Tape removal
6. Outer glove removal
7. Tyvek removal
8. Respirator removal
9. Respirator/hardhat/goggle wash (as necessary)
10. Inner glove removal
11. Soap and water for hand and face wash

12. Supplies available for final cleaning of respirator and goggles.

7.1.3 SAMPLE BOTTLES

Sample bottles will be decontaminated by immersing the bottle in an Alconox and water solution and potable water rinse (i.e., sample bottles will pass through the personnel decontamination line). All coolers will pass through the personnel decontamination line when leaving the exclusion zone.

8.0 PERSONNEL PROTECTIVE EQUIPMENT

The selection of personal protective equipment requires a site specific evaluation of the potential nature and concentration of on-site contaminants. Equipment selected must adequately protect personnel from on-site chemical hazards. However, as protective equipment will cause communications difficulties, limit visibility and increase fatigue/heat stress, the potential for physical injuries increase. It is therefore important to balance increased chemical protection versus increased risk of physical injury and arrive at appropriate selections of equipment to be utilized. On-site contaminant monitoring will allow for confirmation that protective equipment selected is continuously appropriate, or allow upgrading or downgrading of protective equipment as warranted.

8.1 PROTECTION LEVELS

<u>Level C Protection</u>

1. Personnel protective equipment

   - o Air-purifying respirator, full-face, cartridge-equipped (MSHA/NIOSH approved) MSA GMC-H cartridges for organic vapor and High Efficiency Particulate will be utilized.

   - o Chemical-resistant clothing (disposable coated or uncoated Tyvek)

(the SSO will determine whether coated is necessary. Coated will be worn when wet or muddy conditions are present)

- o Gloves (outer), chemical-resistant
- o Gloves (inner), chemical-resistant
- o Boots (outer), chemical-resistant, steel toe and shank
- o Boot covers (outer), chemical-resistant (disposable)*
- o Hard hat
- o Escape mask*
- o 2-Way radio communications*

* Optional

2. Criteria for selection

Meeting all of these criteria permits use of Level C protection:

- o Total airborne hydrocarbons are under the action level
- o Oxygen concentrations are not less than 19.5 percent by volume.
- o Measured air concentrations of identified substances will be reduced by the respirator below the substance's threshold limit value (TLV) and the concentration is within the service limit of the cartridge.

- o Atmospheric contaminant concentrations do not exceed IDLH levels.

- o Atmospheric contaminants, liquid splashes, or other direct contact will not adversely affect any body area left unprotected by chemical-resistant clothing.

- o Job functions do not require self-contained breathing apparatus.

3. Guidance and selection

a. The main selection criterion for Level C is that conditions permit wearing air-purifying respirators.

The air-purifying device must be a full-face respirator (MSHA/NIOSH approved). Cartridges must be able to remove the substances encountered.

In addition, an air-purifying respirator can be used only if:

- o Substance has adequate warning properties.

- o Individual passes a qualitative fit-test for the mask.

- o Appropriate cartridge is used, and its service limit concentration is not exceeded.

b. An air surveillance program is part of all operations when atmospheric contamination is known or suspected. It is particularly important that the air be thoroughly monitored when personnel are wearing air-purifying respirators. Periodic surveillance using direct-reading instruments is needed to detect any changes in air quality necessitating a higher level of respiratory protection.

Level D Protection

1. Personnel protective equipment

- Inner and outer chemically resistant gloves
- Coated or regular Tyvek coveralls (SSO determines which is appropriate, coated shall be used when wet)
- Boots/shoes, leather or chemical-resistant, steel toe and shank
- Safety glasses or chemical splash goggles or face shield
- Hard hat

9.0 GENERAL SITE PRACTICE/POLICIES

- The Project Manager and/or Site Safety Officer shall hold a site safety meeting with all field personnel (including subcontractor personnel assigned to field work) before work commences. During the meeting, all personnel shall be provided with a copy of this Safety Plan; the Plan shall be reviewed and discussed, and questions will be answered. Singed Compliance Agreement forms shall be collected by the Project Manager and filed. Individuals refusing to sign the form will not be allowed to work on the project.

- The personal protective equipment specified in this Plan must be provided to all field personnel. If respirators are specified, personnel shall be informed that facial hair that interferes with proper fit of respirators must be removed. The facial hair requirements comply with OSHA regulations.

- o Subcontractors must provide the protective equipment specified in this plan to all their on-site personnel.

- o All field personnel must inform the Project Manager or his/her designated representative before commencing work at this site. At least two members of the field crew must be on-site whenever work is to be performed.

- o A daily log shall be used to record entry and exit dates and times of all WCC and subcontractor personnel, and of project sit visitors, accidents, illnesses, incidences of safety infractions by field personnel, air quality and personal exposure monitoring data, and other safety-related matters. In case of an accident, injury, or illness occurring during site operations, the Incident/Accident Report form included as part of this Plan must be completed.

- o Smoking, eating, drinking, and open fires (including matches, lighters, etc.) shall not be permitted while working, or in any portion of the site restricting such activities (exclusion and contaminant reduction (decontamination) area).

- o Whenever possible, field personnel should work from a position upwind of borings and while samples are being collected.

- o A safety station containing at least one First Aid Kit, fire extinguisher, eyewash station, burn blanket, and escape pack will be available at the support zone.

9.1 SITE ENTRY

All site entry (and exiting) will occur at a predesignated decontamination station, which will be located at the edge of the designated contamination reduction area. All personnel protective clothing and respirators will be fit tested, condition checked, and (as necessary) donned prior to site entry.

9.2 LEAVING THE SITE

Procedures for leaving the site are will be planned before entry. In addition to decontamination, provision will be made for safe packing of reusable protective clothing; safe packing and site storage of disposable gear; handling of samples and preparation of samples for shipment; and transfer of equipment, gear, and samples from the contaminated area to the clean area.

These are not secure sites, so the Site Safety Officer will assure that all team members have been accounted for at the end of the day.

9.3 UNSAFE SITUATIONS

All employees are directed to bring to the attention of the most readily accessible person in the Health & Safety Chain-of-Command (PM-HSO-SSO) any unsafe condition, practice, or circumstance associated with it resulting from investigations. In cases of immediate hazard to the employees or the public, any employee on the scene should take all practical steps to eliminate or neutralize the hazard; this may include leaving the site. Follow-up consultation with the Project Manager will be made as soon as possible. In such circumstances, the Project Manager will (following consultation with Du Pont) take, or cause to be taken, the necessary steps to ensure that the investigation can be completed safely. Such steps may include changes in procedure, removal or neutralization of a hazard, consultation with a Corporate Health and Safety Officer, consultation with appropriate experts, or bringing in emergency response specialists such as fire department and police department personnel. If the hazard is not immediate, field personnel will consult the Site Safety Officer regarding appropriate corrective measures. Application of this rule requires that all field investigations team members exercise good judgement and common sense.

9.4 INSPECTION AND FIELD OPERATION AUDITS

Inspections and field operation audits are an integral function of this and any health and safety program. The normal responsibility of inspections and audits lies with the Health and Safety Officer. On these projects audits, if performed, will be performed by a Corporate Health and Safety Officer. Primary areas for these audits are defined below:

o Equipment

All equipment and tools will be inspected visually before and after use. Equipment not suitable for further use will be tagged, designating reason for non-use, or discarded immediately. Equipment requiring inspection includes drill rigs, vehicles, organic vapor monitoring equipment, supplied air systems, personnel health and safety equipment, fire extinguishers, and other items for use in field operations.

o Field Audits

Field operation audits (if performed) will be conducted by the Health and Safety Officer for all operations conducted in connection with the investigation. All deficiencies will be recorded and recommendations submitted for corrective action. Recommendations are to be submitted within 24 hours, accompanied by a written report of corrective action by the Field Investigations Manager. All recommendations are to be reviewed by the Health and Safety Officer.

o Special Inspection Procedures

All air-purifying respirators and supplied air systems will receive inspection when fitting and cleaning, and air-purifying respirators will receive positive and negative tests by individual field personnel in accordance with their training every time donned and shall comply with the requirements of 29 CFR 1910.134.

10.0 MEDICAL SURVEILLANCE AND TRAINING

All WCC personnel involved with the field investigations on contaminated or potentially contaminated sites are part of our Employee Medical Surveillance Program (EMSP). The EMSP is designed to evaluate whether an employee's health allows them to undergo the physical stress involved in hazardous site work, as well as to track variations in health indicators.

The local physician (Dr. Eddy Bresnitz, Occupational Health Services, Medical College of Pennsylvania -- (215 842-6540) for WCC's Plymouth Meeting Office will serve as physician for follow-up medical testing should chemical exposure incidents occur during field operations for this project. Immediate health care for exposure or trauma incidents will be obtained at the hospitals designated in this HASP.

Subcontractor personnel must be part of a medical monitoring program which at a minimum addresses requirements of 29 CFR 1910.134 and 29 CFR 1910.120. Documentation of subcontractor medical surveillance programs must be supplied to the Plymouth Meeting Health and Safety Officer (BUHSO) in advance or the SSO.

All personnel must have attended WCC Basic Health and Safety training or an approved equivalent. Subcontractor personnel must supply documentation of training to the BUHSO or SSO.

11.0 EMERGENCY RESPONSE EQUIPMENT AND PROCEDURES

In the event of a safety or health emergency at a site, appropriate corrective measures must immediately be taken to assist those who have been injured or exposed and to protect others from hazard. Emergency personnel will be notified of the incident immediately. If necessary, first aid will be rendered.

11.1 IN THE EVENT OF AN EMERGENCY

1. Notify ambulance, police, fire department, and hospital as soon as possible.

2. Immediately remove injured or exposed person or persons from danger. In all cases professional help must be summoned.

3. Decontaminate, if necessary, and render first aid to affected personnel.

4. All other personnel on-site should be evacuated from area until the Field Investigations Manager gives the instruction to resume work, after he or she has determined that it is safe to do so.

5. Within 24 hours, a detailed account of the incident, (as per the forms in this HASP including corrective action to be taken, will be forwarded by the Field Investigations Manager or Health and Safety Officer for review by the Health and Safety Committee.

6. A formal accident investigation report will be prepared within 7 days and submitted for review by the Health and Safety Committee.

7. Report of incident will be submitted to Du Pont.

Preparation for contingencies depends upon a realistic evaluation of worst case scenarios and likely events based on the proposed level of effort and the environmental conditions at the site. Clearly, contingency procedures must anticipate physical and chemical injuries, as well as heat stress incidents when impermeable protective clothing is worn. Distinct emergency and injury prevention networks must be developed for each of these possibilities, including the development of emergency transportation systems, identification of medical centers, notification protocols, first aid/CPR and protocols for identifying specific chemical exposures.

Physical injuries in the form of sprained ankles or backs, puncture wounds, or broken bones are nearly unavoidable despite safety awareness and training. The preponderance of jagged metal, uneven terrain, construction debris, heavy lifting, and encumbered movement due to protective equipment increases the likelihood of physical injuries.

Significant chemical exposures are probably less likely to occur due to the conservative precautions already taken in the form of respiratory and cutaneous protection. For chemical injuries, on-site first aid is largely limited to the use of eyewashes, deluge showers, and oxygen inhalators. In anticipating a chemical injury, emphasis should be placed on location and maintenance of first aid equipment and developing protocols for its use. An additional network should be developed for identifying the chemical agent(s) to which the worker(s) may have been exposed.

The uncontrolled release of chemical vapors or a configuration that threatens on-site personnel of the public is clearly a worst case situation that must be anticipated. The most likely cause for evacuation is fire and/or explosion from a spark or chemical reaction, although some scenarios may also include uncontrolled releases of volatile vapors (ruptured or leaking barrels can generally be covered or contained before the incident escalates to evacuation status). Although drummed wastes are not expected to be encountered at the site, the potential for fire and/or explosion still exists due to the volatile nature of suspected contaminants which may be encountered during site investigations. Fire extinguishers are available on all site vehicles. Fire department emergency numbers will be prominently posted.

11.2 EVACUATION AND HAZARDOUS SITUATIONS

(Adapted from "Hazardous Materials Spill Monitoring," EPA-4-79-008a, January 1979).

This section describes the actions that will be necessary if evacuation of an area is required and contains information that personnel will need in hazardous situations.

11.2.1 RESPONSIBILITIES IN AN EVACUATION SITUATION

It should be noted that the Health and Safety Committee responsibility is only advisory and does not include direct evacuation involvement. It is the responsibility, however, of the Health and Safety Officer or Site Safety Officer to assess the emergency, to determine if an evacuation potential exists, and to inform state and/or local officials of conditions. Although the decision of when and where to evacuate persons is primarily the responsibility of state and local health officials and emergency organizations, the Health and Safety Officer must provide guidance on actual or anticipated ambient air concentrations that would be immediately injurious to the public.

A Corporate Health and Safety Officer will also provide guidance to determine when conditions no longer warrant an evacuation potential, or when ambient concentrations have permanently decreased below the evacuation trigger concentration. Judgmental decisions should be made jointly by local emergency units, and township administration.

11.2.2 CHEMICAL EMERGENCY INFORMATION SOURCES

Chemical emergency information sources include the following:

- Coast Guard Chemical Hazards Response Information System (CHRIS). This system consists of four manuals, a computer-assisted hazard-assessment system, and Coast Guard technical assistance.

- CHEMTREC System, which has warning and guidance on over 3,600 items classed by chemical and trade name. CHEMTREC can be accessed through its emergency telephone number: 800-424-9300 (483-7616 in Washington, D.C.) Although the system is specifically oriented toward transport, it is a valuable repository of information for any incident of environmental degradation caused by a specific chemical agent, if known.

11.2.3 COMPLICATING CONDITIONS AT HAZARDOUS WASTE SITE

The hazards presented by hazardous materials may be either intensified or ameliorated by local conditions at the site. Weather conditions, fire (actual or potential) or other conditions may require modification of basic monitoring approaches. Such factors may superimpose additional restrictions on monitoring and clean-up operations by affecting the nature and rate of movement of materials within and beyond the immediate area, the toxicity and reactivity of hazardous substances, and the monitor's mobility within the working area.

11.2.3.1 WEATHER

Wind increases the dispersal of toxic gases, powders, and aerosols from the hazardous waste site. Downwind monitoring will be conducted during all drilling activities.

Precipitations is often a mixed blessing at a hazardous materials site. On the positive side, it can dilute toxic material concentrations, cool potential reactants, and suppress the aerial dispersion of powders and aerosols. On the other hand, rain increases sheet runoff and waterborne dispersal; causes spread of many materials, including combustible liquids; causes slippery working conditions; and may react with alkali metals, anhydrous powders, concentrated acids, some organics, etc., to yield heat, fire, spattering, gases, or toxic fumes.

High ambient temperatures increase volatilization and chemical reaction rates. The likelihood of explosive gas concentrations and toxic reaction products increases with increasing temperature. High temperatures also increase the personnel fatigue factor and therefore the possibilities of potentially dangerous judgment errors. As judgment, training, and common sense are the worker's primary safeguards, on-site supervisors and working-level personnel should recognize the signs of fatigue and remove themselves to rest areas for recuperation.

12.0 LOGS, REPORTS, AND RECORDKEEPING

Implementation of the provisions of this Health and Safety Plan must be completely documented. The SSO will set up a separate file to receive health and safety related record and activity reports. This file will contain the following records:

1. Copies of the WCC Health and Safety Compliance Agreement documenting health and safety briefings and personnel signatures;

2. Copies of safety equipment operation manuals;

3. Records of usage and calibration of environmental monitoring equipment;

4. Employee injury/exposure incident reports;

5. Records of safety violation and remedial actions taken, and

6. Documentation of subcontractors' compliance with WCC requirements for health and safety training and medical monitoring.

A health and safety field logbook will be maintained on-site and should contain such information as: weather conditions, employees and visitors on-site, level of personal protection worn, monitoring instrument readings (average, peak, and background), and subjects discussed during site health and safety briefings and names of attendees.

All field personnel, including subcontractors, must sign the WCC Employee Health and Safety Compliance Agreement indicating that they have attended a briefing by the SSO, and that they understand and agree to abide by the provisions of this HASP.

WM-5"O"

APPENDIX A

HEAT AND COLD STRESS PREVENTION AND MONITORING

HEAT AND COLD STRESS MONITORING

The requirements of personal protective equipment may create heat stress. Heat st4ress symptoms may occur at any level of protection, but they are especially common in Level B and C protective clothing. This safety plan addresses heat and cold stress, although due to the season of field operations, no problems are anticipated.

MAXIMUM WEAR/WORK TIME IN FULLY ENCAPSULATING OR SEALED BARRIER PROTECTIVE GARMET

Ambient Temperature	Maximum Wearing Time (hr)
Above 90° F	0.25
85° - 90° F	0.50
80° - 85° F	1.00
70° - 80° F	1.50
60° - 70° F	2.00
50° - 60° F	3.00*
30° - 50° F	5.00
Below 30° F	8.00

* Anticipated temperatures during field investigations

WCC will develop a work/rest schedule for Levels B and C using this information for guidance, if heat/cold stress monitoring is required due to unexpected climatic conditions. Monitoring, if required, will include periodic checks of respiration, heart rate, blood pressure and body temperature (oral).

Heat Stress

Heat stress is a function of heat and humidity. A worker's susceptibility to heat stress can vary according to his/her physical fitness, perspiration rate, degree of acclimatization to hot weather, age and diet.

Prevention

Institute the following steps to prevent overexposure of workers to heat:

1) Maintain body fluid levels by encouraging workers to drink large amounts of water - - more than necessary to satisfy thirst. (1 to 2 cups every 15 to 20 minutes, or at each monitoring break - - see Table A-1). The water temperature should be maintained at 50° to 60° F. To maintain body salts, food should be liberally salted, and a 0.1 percent salt solution should be available as drinking water for unacclimatized workers.

2) Adjust work schedules if necessary, providing adequate rest periods. When feasible, rotate personnel and perform work during the cooler hours of the day.

3) Provide a cool shelter (air-conditioned, preferably) or shaded areas for rest periods. The shelter should be close to the work area.

4) Provide cooling devices such as ice vests and field showers.

5) Maintain an optimal level of worker fitness by encouraging regular exercise, proper diet, etc. If possible, acclimatize workers to site conditions for several days before work begins.

Monitoring

For workers wearing impermeable clothing, institute heat stress monitoring when the ambient temperature is 70° F or above, and/or if humidity is high. Use the schedule in Table A-1 to decide on the frequency of monitoring. Heart rate, oral temperature, and body weight should be measured as shown in Table A-2. This table also sets forth actions to be taken if these indicators exceed certain limits.

In addition, personnel should be aware of the symptoms of heat stress as listed in Table A-3.

Cold Stress (Hypothermia)

Cold stress is a function of cold, wetness and wind. A worker's susceptibility to cold stress can vary according to his/her physical fitness, degree of acclimatization to cold weather, age, and diet.

Prevention

Institute the following steps to prevent overexposure of workers to cold:

1) Maintain body core temperature at 96.8° F or above by encouraging workers to drink warm liquids during breaks (preferably not coffee) and wear several layers of clothing. Wool is recommended since it can keep the body warm even whenthe wool is wet.

2) Avoid frostbite by adequately covering hands, feet, and other extremities. Clothing such as insulated gloves or mittens, earmuffs, and hat liners should be worn. To prevent contact frostbite (from touching metal and cold surfaces below 20° F), workers should wear anti-contact gloves. Tool handles and control bars should be covered with insulating material.

3) Adjust work schedules if necessary, providing adequate rest periods. When feasible, rotate personnel and perform work during the warmer hours of the day.

4) Provide a heated enclosure for workers close to their work area. Workers should remove their outer layer(s) of clothing while in the shelter to allow for sweat evaporation.

5) In the event that wind barriers are constructed around an intrusive operation (such as drilling), the enclosure must be properly vented to prevent the build-up of toxic or explosive gases or vapors. Care must be taken to keep any heat source away from flammable substances.

6) Using a wind chill chart such as the one in Table A-4, obtainthe equivalent chill temperature (ECT) based on actual wind speed and temperature. Refer to the ECT when setting up work warm-up schedules, planning appropriate clothing, etc. Workers should use warming shelters at regular intervals at or below an ECT of 20° F. For exposed skin, continuous exposure should not be permitted at or below an ECT of -25° F.

7) Workers who become immersed in water or whose clothing becomes wet (from perspiration, rain, etc.) must immediately be provided a change of dry clothing whenever the air temperature is 35.6° F or below.

8) Maintain an optimal level of worker fitness by encouraging regular exercise, proper diet, etc. If possible, acclimatize workers to site conditions for several days before work begins.

Monitoring

Personnel should be aware of the symptoms of cold stress. If the following symptoms of systemic hypothermia are noticed in any worker, he/she should immediately go the warm shelter:

- o heavy, uncontrollable shivering
- o excessive fatigue or drowsiness
- o loss of coordination

o difficulty in speaking

o frostbite (see below)

Frostbite is the generic term for local injury resulting from cold. The stages of frostbite and their symptoms are as follows:

1) Frostbite or incipient frostbite
- sudden blanching or whitening of the skin

2) superficial frostbite:
- waxy or white skin which is firm to the touch (tissue underneath is still resilient)

3) deep frostbite:
- tissues are cold, pale, and solid

APPENDIX

INCIDENT REPORT FORM

Form HS-502
HAZARDOUS WASTE INCIDENT REPORT

Date ________ Project/ Location ______________________ Business Unit ______________

DESCRIPTION OF INCIDENT, INCLUDING INJURIES, PROPERTY DAMAGE AND EMERGENCY ACTION TAKEN AND PERSONNEL INVOLVED (use additional sheets if needed):

____
____
____
____
____

WITNESSES OF INCIDENT:

____
____
____

POSSIBLE OR KNOWN CAUSES:

____
____
____

WHAT ACTIONS ARE NEEDED TO PREVENT A SIMILAR INCIDENT?

____
____
____

REPORTER ______________________ BUSINESS UNIT SAFETY OFFICER ______________________

PROJECT MANAGER ______________________ CORPORATE HEALTH AND SAFETY OFFICER ______________________

APPENDIX

EMERGENCY INFORMATION

AND

HOSPITAL ROUTE MAP

APPENDIX

PROJECT SAFETY DOCUMENTATION

TABLE A-1[1]

REQUIRED FREQUENCY OF HEAT STRESS MONITORING FOR WORKERS IN IMPERMEABLE CLOTHING

Adjusted[2] Temperature (^{o}F)	Work Time Allowed Before Monitoring Break (min.)
90 or above	15
87.5 - 90	30
82.5 - 87.5	60
77.5 - 82.5	90
72.5 - 77.5	100

(1) Adapted from Eastern Research Group and National Institute for Occupational Safety and Health, Occupational Safety and Health Guidance Manual for Superfund Activities, September 26, 1984, pp. 8-76.

(2) Calculate the adjusted air temperature (ta adj) by using this equation:

$$Ta\ adj\ ^{o}F = Ta\ ^{o}F + (13 \times \text{percent sunshine})$$

Measure air temperature (Ta) with a standard thermometer, with the bulb shielded from radiant heat. Then estimate percent sunshine (100 percent sunshine = no cloud cover and a sharp, distinct shadow; 0 percent sunshine = no shadows).

Table A-2

Heat Stress Indicator	When to Measure	If Exceeds. . .	Action
Heart rate (pulse)	Beginning of rest period	110 beats per minute	Shorten next work period by 33 percent
Oral tempertaure	Beginning of rest period	99°F (after thermometer is under tongue for 3 minutes)	Shorten next work period by 33 percent
		100.6° F	Prohibit work in impermeable clothing
Body weight	1. Before workday begins (a.m.) 2. After workday ends (p.m.)	(weight loss) 1.5 percent of total body weight	Increase fluid intake

TABLE A-3[1]

SYMPTOMS OF HEAT STRESS

Heat rash results from continuous exposure to heat or humid air.

Heat cramps are caused by heavy sweating with inadequate fluid intake. Symptoms include:

- muscle spasms
- pain in the hands, feet, and abdomen

Heat exhaustion occurs when body organs attempt to keep the body cool. Symptoms include:

- pale, cool, moist skin
- heavy sweating
- dizziness

Heat stroke is the most serious form of heat stress. Immediate action must be taken to cool the body before serious injury and death occur. Symptoms are:

- red,hot, dry skin
- lack of perspiration
- nausea
- dizziness and confusion
- strong, rapid pulse
- coma

---

(1) Reproduced from Occupational Safety and Health Guidance Manual for Superfund Activities (see Table A-1), p. 8-79

TABLE 4-1

NORTH DISPOSAL SITE
WASTE DISPOSAL INVENTORY

Material	Estimated Quantity
Garbage	several tons
Trash (glass, wood, paper, cardboard)	100 tons
Steel drums	several hundred tons
Lever Packs	several hundred tons
Sand and dirt	several thousand tons
Concrete	
Steel work	
Asbestos	5 tons
Light ballasts - PCB's/PBB's	2 tons
Rubber - gasket material, tires from garage	a few tons
Nylon shutters	2 tons
Artificial marble - "Corian"	4 tons
Acrylates and latex emulsions	several hundred lbs
Quinacridone tars	1,000 tons
Bad quality copper phythalocyanine pigment	100 tons
Bad quality quinacridone pigment	
Bad quality "Afflair" pigment	estimated 10,000 - 15,000 lbs
Bad quality Chromium Dioxide coated "Mylar" recording tape	6 tons
"Afflair" fines (30 percent mica) plus (70 percent TiO_2)	estimated 100,000 lbs
Bad quality chromium dioxide floor sweeping and bags	2 tons
Thoriated nickel	20 tons of combined waste
Dirt contaminated with zinc ore	several hundred tons

TABLE 4-1 (Continued)

Material	Estimated Quantity
Raw materials left in bag liners and drums and leaks from drums	several hundred tons
- Quinacridone	a few tons
- Copper phthalocyanine	a few tons
- "Afflair"	a few tons
- Magentic products	a few tons
Laboratory waste including resins from Quinacridone, copper phthalocyanine, "Afflair", and magnetic products	a few tons

Scrap amounts of the following materials (maximum several tons).

- Graphite (thick pieces–carbon 3' x 1-1/2' rock) plus shavings and powder
- Titanium - metal
- Sodium (burned or exploded)
- "Baxtron" (tungsten carbide cobalt)
- "Tiper-sul" (potassium titanate (PKT)
- "Fibex" (TiO_2)
- "Erifon"
- Silica
- Silicon
- Zirconium
- Columbium
- Titanium bisteric - synthetic oil - antifreeze
- Tetra-isopropyltitanate

WCC EMPLOYEE HEALTH AND SAFETY COMPLIANCE AGREEMENT

I, the undersigned, have received a copy of the Health and Safety Plan identified below. I have read the plan, understand it, and agree to comply with all of the health and safety directives. I have attended a site briefing given by the Site Officer or Health and Safety Officer. I understand that I may be prohibited from working on the project for violating any of the directives, policies or procedures detailed within this SHERP.

PROJECT No.: 87C2665

SITE NAME: Du Pont Newport Landfill; Newport, Delaware

Firm: ______________________________

______________________________ ______________________________
Signature Date

HEALTH AND SAFETY PLAN
FOR
DU PONT NEWPORT LANDFILL
NEWPORT, DELAWARE

Plan Approval:

Alfred M. Hirsch ______________________ 16 June 87 __________

Alfred M. Hirsch, Ph.D. — Date
Project Manager

Robert G. Ehlenberger ______________________ 6/17/87 __________

Robert G. Ehlenberger — Date
Business Unit Health and Safety Officer

Phillip L. Jones ______________________ 6/17/87 __________

Phillip Jones, CIH — Date
Corporate Health and Safety Officer

TABLE A-4(1)

COOLING POWER OF WIND ON EXPOSED FLESH
EXPRESSED AS AN EQUIVALENT TEMPERATURE (UNDER CALM CONDITIONS)

Estimated Wind Speed (in mph)	Actual Temperature Reading (°F)											
	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
	Equivalent Chill Temperature (°F)											
calm	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
5	48	37	27	16	6	-5	-15	-26	-36	-47	-57	-68
10	40	28	16	4	-9	-24	-33	-46	-58	-70	-83	-95
15	36	22	9	-5	-18	-32	-45	-58	-72	-85	-99	-112
20	32	18	4	-10	-25	-39	-53	-67	-82	-96	-110	-121
25	30	16	0	-15	-29	-44	-59	-74	-88	-104	-118	-133
30	28	13	-2	-18	-33	-48	-63	-79	-94	-109	-125	-140
35	27	11	-4	-20	-35	-51	-67	-82	-98	-113	-129	-145
40	26	10	-6	-21	-37	-53	-69	-85	-100	-116	-132	-148
(Wind speeds greater than 40 mph have little additional effect.)	*LITTLE DANGER* In < hr with dry skin. Maximum danger of false sense of security				*INCREASING DANGER* Danger from freezing of exposed flesh within one minute.				*GREAT DANGER* Flesh may freeze within 30 seconds.			
	Trenchfoot and immersion foot may occur at any point on this chart.											

...loped by U.S. Army Research Institute of Environmental Medicine, Natick, MA.

(1) Reproduced from American Conference of Governmental Industrial Hygienists, Threshold Limit Values and Biological Exposure Indices for 1985-1986, p. 101.